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Cost-Constrained Optimization of Energy Efficiency for Multi-family and Commercial Buildings

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ABSTRACT

This project provides California stakeholders with cost-optimized selections of technology packages for building cost-effective and high-efficiency multi-family residential and commercial buildings. A detailed cost and energy performance analysis was used to identify measures and packages that most closely approach zero-net energy for each building type in each state climate zone. A detailed analysis of the direct and indirect carbon emissions of each building was used to estimate the additional construction cost-per-metric tons of CO_2e saved by the recommended package. EnergyPlus models were developed with simulated prototype upgrades in energy efficiency, photovoltaic systems, and battery energy storage systems for various commercial and multifamily buildings. The simulation results analyzed building performance according to 2022 time-dependent value (TDV)-based cost-effectiveness, additional construction cost per metric ton CO_2e reduction, and change in the operating utility bill, including eligibility for different tariffs. Policymakers should be able to use these modeling results to accelerate adopting cost-optimized measures through codes, standards, and incentive programs. Building developers and designers should be able to use the cost-benefit analysis for their building type and climate zone to inform their decisions on how to improve building designs by targeting the most TDV cost-effective measures. Moreover, the method developed and used may allow other interested stakeholders to do their own cost-effectiveness analyses using the model prototypes, measures, and analysis tools developed in this project and made publicly available.

Keywords: Cost-effective ZNE-TDV, Energy Efficiency, Construction Cost, Operating Cost

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EXECUTIVE SUMMARY

Background

A Zero-Net Energy (ZNE) building is a building where the total amount of energy used by the building on an annual basis is equal to the amount of renewable energy created on the site. Previous studies have investigated how close various new construction commercial buildings can approach ZNE, with much of the answer depending upon the ratio of potential solar panel area to building energy needs.

Policymakers need ZNE modeling results to accelerate the adoption of cost-optimized measures through codes, standards, and incentive programs. Building developers and designers should be able to use the cost-benefit analysis for their building type and climate zone to inform their decisions on how to improve building designs by targeting the most cost-effective measures to obtain the maximum percentage of energy savings toward ZNE. Moreover, the ZNE modeling tools may allow other interested stakeholders to do their own cost-effectiveness analyses using the publicly available models, costs, and analysis methods developed in this project.

Project Purpose and Approach

The major objectives of this work were: a) to guide policy and code development, b) to inform building designers in a general manner, and c) to assemble and develop simulation tools for modelling different energy efficiency measures as needed. This work did not produce an individual-building design tool, nor prescriptive packages for meeting ZNE.

The first order of business for this study was to choose appropriate definitions for ZNE and cost-effectiveness. Some options for defining ZNE included site energy, source energy, and the hourly changing value of electricity, also called Time Dependent Valuation (TDV). Some options for cost-effectiveness include construction cost along with utility bill operating cost or TDV dollar value. The authors choose TDV 2022, developed by the California Energy Commission with Energy and Environmental Economics, for both the ZNE and cost-effectiveness metrics to make apples-to-apples comparisons. The performance of the TDV optimum upgrade packages was also calculated according to a utility-bill metric, as well as the cost of conserved greenhouse gas emissions.

The analysis was centered on Energy Plus simulations of various commercial and multi-family building prototypes across all 16 California climate zones. The modelled buildings were based upon the Department of Energy (DOE) EnergyPlus commercial-building prototypes, modified to match California Title-24 2019 prescriptive requirements and common design practices in California. The team did not modify the HVAC system architecture, controls, schedules, window to wall ratios, or geometry, nor did they consider changes in maintenance costs or changes in expected lifetime. Natural-gas technology options were not included. The building types investigated in this report were selected because they are predicted to experience significant new construction in the coming decade, and they span the range of common building attributes that are likely to impact the feasibility of reaching ZNE cost-effectively. The types of buildings range from single-story low-rise commercial buildings to large multi-story commercial office buildings, as well as high-rise multi-family buildings, which encompass large roof area down to the small roof area per building floor area. The types of HVAC systems range from central built-up systems to distributed packaged units. The magnitude of internal energy consumption and waste heat generation per square foot ranges from very low to very high. The occupancy schedules range from weekday, day and late evening, to nights and weekends, to significant occupancy at all times. Covering these broad ranges of building attributes does a reasonable job of spanning the key parameters affecting the ability to meet ZNE cost-effectively. The seven building types selected were:

- Large Office
- Quick-Service Restaurant
- Stand-Alone Retail
- Full-Service Restaurant
- Strip Mall
- Warehouse
- High-Rise Multifamily Residential

Simulations were used to estimate the interactive effects of more than 50 energy efficiency upgrades above 2019 Title 24 requirements, and to compare the TDV cost-effectiveness of these upgrades with the TDV cost-effectiveness of on-site solar and on-site battery systems. This study competes efficiency upgrades, solar, and batteries against each other including interactions between all relevant efficiency upgrades to select upgrade packages for optimum TDV cost-effectiveness. True competition between upgrades to be included in the optimum packages is a significant difference between this study and previous narrower ZNE cost-effectiveness studies.

Key Results

The major technical results include:

- The most cost-effective energy efficiency upgrades actually lower construction costs while reducing TDV energy costs because they reduce the size and cost of the required HVAC systems (such as upgrading to high efficacy LED lighting systems with 130 lumens per watt from a baseline of linear fluorescent). High-performing efficiency upgrades, which are often more cost-effective than batteries or solar, are listed in Table ES-1.
- Most energy efficiency upgrades increased construction costs. TDV benefit-to-cost ratios for the efficiency upgrades calculated as TDV $ saved per $ additional construction cost depend on climate zone and building type as well as interactions with other upgrades. TDV benefit-to-cost ratios for individual efficiency upgrades include:
    - The most cost-effective efficiency upgrades reduce the size and cost of required HVAC systems enough to result in reduced construction costs, thereby saving TDV at zero or negative cost.
    - Very cost-effective efficiency upgrades that almost paid for themselves with HVAC size reduction savings produced very small increases in construction costs, and achieved benefit to cost ratios of 15 to 5700.
    - Efficiency upgrades had to achieve benefit to cost ratios of 1.0 or more to be minimally TDV cost-effective.

- Roof mounted solar PV produced TDV benefit to cost ratios of 2.0 to 3.9, depending upon climate zone TDV-factor shapes.
- On-site batteries produced TDV benefit to cost ratios of 1.3 to 2.3, depending upon climate zone TDV-factor shapes.

- Energy efficiency investments accounted for a relatively small fraction of the investment required to reach TDV-ZNE, varying significantly with climate zone and building type:
  - Standalone Retail ⇨ **5.6 percent to 20 percent** when combined with solar PV, and **4.3 percent to 33 percent** when combined with batteries.
  - Large Office ⇨ **0.06 percent to 4.9 percent** when combined with batteries.

Table ES-1: Energy Efficiency Upgrades Ranked by TDV Cost-Effectiveness

Efficiency Upgrade	TDV Cost-Effectiveness across building types and climate zones
LED lighting (high efficacy)	**Often Construction Cost Savings**
LED lighting (very high efficacy)	**Often more TDV cost-effective than Batteries or Solar**
Supply duct sealing	
Indirect evaporative pre-cooling of ventilation air	
Evaporative pre-cooling of condenser air	
Water heaters (heat pump, gas storage tank)	
Air to water heat pump for heating hot water circulation loops*	
Condensing boiler	

Source: University of California, Davis

Roof mounted solar and batteries are TDV cost-effective in all California climate zones for all building types. The results show that all the commercial buildings studied can reach ZNE-TDV cost-effectively with TDV cost-effective energy efficiency upgrades plus large batteries when allowed to charge from the grid and discharge to the grid and operated to charge during three-hour periods with the lowest TDV factors and to discharge during the highest TDV factor hour. Battery systems save TDV $ but in some climate zones increase utility bills due to tariff structures

TDV cost-effective energy efficiency upgrades plus rooftop solar can reach ZNE-TDV cost-effectively in all the single-story commercial buildings studied, other than restaurants. Further conclusions include the following:

- Solar systems save TDV $ and reduce utility bills by enough to decrease the net present value of upgrades incremental construction cost plus utility bill costs over a 30-year period.

- For restaurants, the combination of small, gabled roofs limiting solar system capacity, and very high energy use intensity leading to high upgrade costs, resulted in an increase in utility bills in some climate zones.
- In high-rise buildings there is not sufficient roof space for TDV cost-effective efficiency upgrades plus solar to reach ZNE-TDV. For example, across all climate zones TDV cost-effective efficiency plus rooftop solar achieves a TDV reduction of **29 percent-39 percent** in Highrise Multifamily and **12 percent-22 percent** in the Large Office with large data center energy consumption.
- Timing of energy savings and interactions between energy efficiency upgrades can significantly change TDV cost-effectiveness of efficiency upgrades compared to an average annual energy savings analysis of individual measures.
- Few efficiency upgrades are more cost-effective than building-scale solar or batteries, likely because code requires many of the cost-effective strategies and because solar and battery systems are cost-effective competition for the remaining upgrades.
- Meeting ZNE-TDV in ways that are TDV cost-effective does not imply energy-bill cost effectiveness, nor cost-effective reduction in greenhouse gas emissions
    - For TDV cost-effective efficiency plus battery upgrades where batteries discharge at the highest TDV value times, and charge at the lowest TDV value times, utility bills increase for multiple building types in multiple climate zones using existing utility tariff structures.
    - For individual efficiency upgrades, the additional construction cost per tonne of carbon dioxide equivalent long run marginal greenhouse gas saved over 30 years fell into the following ranges across climate zones and building types:
        - Individual Efficiency Upgrades ⇨ $0 to $1,991
        - Solar ⇨ $632 to $1344
        - Batteries ⇨ $424 to $497
- 2022 TDV favors Natural Gas over Electricity, but heat pumps are sometimes efficient enough to overcome the disfavor to be TDV cost-effective.
- Roof mounted solar systems are a surprisingly expensive way to reduce carbon emissions because they generate energy at times when the long run marginal emissions of the grid are very low or zero (specifically during renewables curtailment periods energy sent to the grid has no emissions savings).

Knowledge Transfer and Next Steps

Moving forward, the simulations performed and the tools developed in this study can be extended and applied further to investigate different ZNE strategies and technologies, different policies based upon different metrics (for example utility-bill cost effectiveness, maximum conserved carbon at different price points), and specific-building design decisions. Issues that this work could help to explore in the future include:

- The carbon abatement cost effectiveness of energy efficiency upgrades in addition to TDV or utility bill cost-effectiveness.
- Impacts of Net Energy Metering tariff rules on the cost-effectiveness of behind-the-meter batteries, including compensation for export at high TDV value times.
- Strategies for decreasing the carbon abatement cost of solar generation with considerations for on-site versus utility scale.

Benefits to California

Building developers, utilities, and policymakers need solutions to evaluate new technologies that will facilitate ZNE in new buildings. These solutions must be applicable to a variety of building types. This project provides optimized recommendations for cost-effective energy savings and on-site generation solutions for a wide variety of California's building portfolio for all 16 climate zones.

This study estimates that at a new construction rate of 127 million square feet of commercial space annually, the adoption rate of cost-effective ZNE measures identified in this report would save California 282 giga-watt hours of electricity and almost 103,000 tons of CO_2 each year.

CHAPTER 1: Introduction

Project Purpose

This project provided California stakeholders with cost-optimized strategies and technology packages for building cost-effective high-efficiency multi-family residential and commercial buildings in each California climate zone. A detailed cost and energy performance analysis was used to identify measures and packages that most closely approach zero-net energy by time dependent valuation (ZNE-TDV) cost-effectively for each building type in each climate zone. A detailed analysis of the direct and indirect carbon emissions of each building was used to augment the cost-optimization. The carbon emissions analysis estimates the carbon impact of the recommended package. The specific objectives of this project were to:

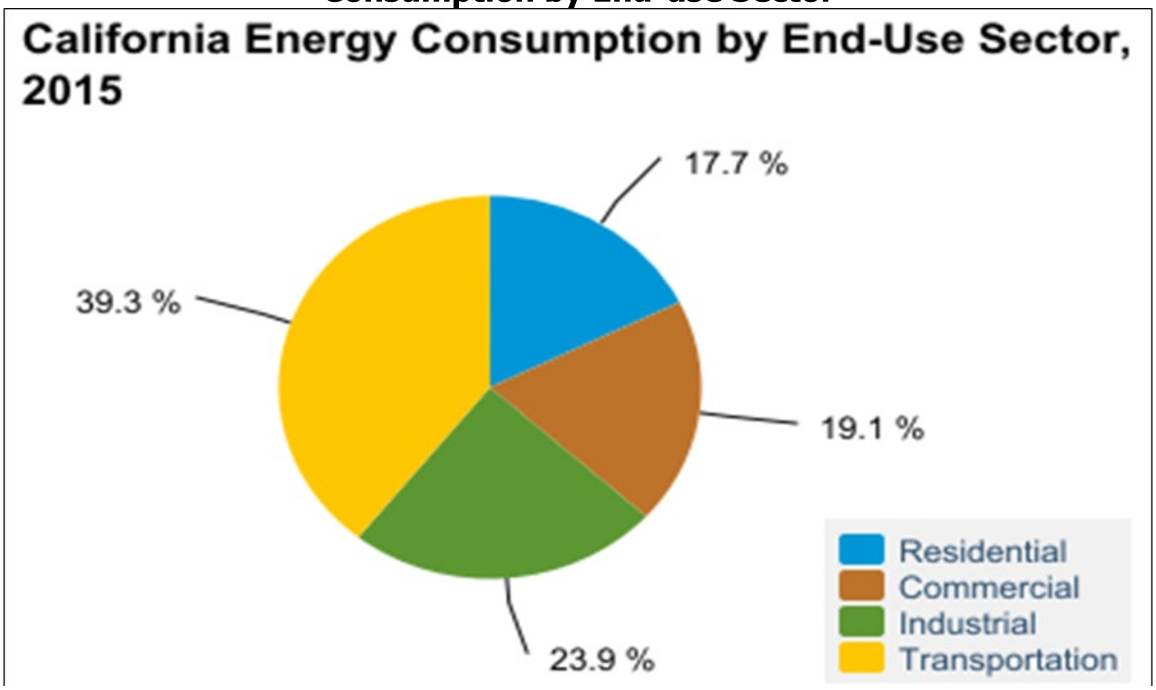
- Develop EnergyPlus models for multiple commercial and multifamily building prototypes representative of baseline California construction.
- Model photovoltaic, battery, and energy efficiency upgrades in applicable building types.
- Run automated simulations of every permutation of building type and climate zone with applicable upgrades.
- Post-process outputs from the simulations, including energy use and indoor conditions.
- Calculate building operation costs based on Time Dependent Valuation for electricity and natural gas.
- Specify construction by measure and building type.
- Determine the maximum cost-effective reduction in net TDV consumption toward ZNE goals.
- Calculate the direct and indirect carbon emissions of each recommended package of measures.
- Calculate the utility bill net present value of each recommended package of measures.

Policymakers should be able to use these modeling results to accelerate the adoption of cost-optimized measures through codes, standards, and incentive programs. Building developers and designers should be able to use the cost-benefit analysis for their building type and climate zone to inform their decisions on how to improve building designs by targeting the most cost-effective measures to obtain the maximum percentage of energy savings toward ZNE. Moreover, the method that was developed and used may allow other interested stakeholders to do their own cost-effectiveness analyses using the publicly available models, costs, and analysis methods developed in this project.

Background

In 2015, 19.1 percent of California's energy was used by the commercial sector and another 17.7 percent was used by the residential sector (Figure 1)[1]. This implies that buildings were responsible for 36.8 percent of the state's total energy use, or 2,822 trillion Btu of the total 7,676 trillion British thermal units (Btu) used (U.S. Energy Information Administration, 2015). The energy from those two sectors cost California nearly $42.8 billion that year. In addition, data shows that 13.2 percent, or 42 million metric tons, of California's CO2 emissions in 2015 came from these two sectors as well (U.S. Energy Information Administration, 2015). There is substantial potential for reductions in energy use, expenses, and emissions within California's building sector.

Figure 1: Energy Information Administration Statistics on California Energy Consumption by End-use Sector



California Energy consumption by sector

Source: U.S. Energy Information Administration (EIA) State Energy Data System

The California Public Utilities Commission (CPUC) states that the top three reasons behind it promoting energy efficiency are: 1) helping reduce greenhouse gas emissions, 2) helping the economy, and 3) avoiding the creation of new power plants and transmission lines (California Public Utilities Commision, 2016). The organization makes it clear that energy efficiency

[1] U.S. Energy Information Administration, 2015.

programs benefit the taxpayers and the environment. These benefits are the CPUC's justification for developing their strategic plan that calls for all new residential buildings to be ZNE by the year 2020 and all new commercial buildings to be ZNE by 2030. This research project will aid the CPUC's plan and help provide those same benefits.

Optimization Metrics and Methods

Definition of Zero-Net-Energy

To evaluate the ability of a building to reach "zero-net-energy," a clear definition of zero-net-energy must be selected. This project uses the definition of ZNE proposed by the California Energy Commission's 2013 Integrated Policy Report (California Public Utilities Commision, 2016). The definition used is:

A Zero-Net-Energy Code Building is one where the net amount of energy produced by on-site renewable energy resources is equal to the value of the energy consumed annually by the building, at the level of a single 'project' seeking development entitlements and building code permits, measured using the California Energy Commission's (CEC) Time Dependent Valuation metric (TDV). A zero-net-energy code building meets an energy use intensity value designated in the Building Energy Efficiency Standards by building type and climate zone that reflect best practices for highly efficient buildings."

This definition describes a zero-net-energy building as one that produces the same or more **energy value** than the amount of **energy value** that it uses in a year. This implies two things: 1) the building can use energy from the grid if it offsets the value of that energy with the value of exported energy that is generated on site, 2) the building can consume more energy than it generates, depending upon the timing of the energy use versus the timing of the energy export. The energy unit that is used in the definition TDV, and as the key metric throughout this study.

Time Dependent Valuation

For every hour of the year, California calculates an expected societal cost of energy, which is reflected in TDV (California Energy Commission, 2017). These societal costs are provided for electricity, natural gas, and propane. The values are intended to reflect the higher societal costs of energy at peak hours and the lower costs at off-peak hours. Some of the specific factors that affect these costs are source energy costs, market energy demand, and the carbon emitted from the energy's production (California Energy Commission, 2017). California currently uses this metric when evaluating Title 24 building codes cost-effectiveness. The purpose of TDV is to reflect the actual cost of energy to society, which may or may not be reflected in the actual cost to the end user.

Greenhouse Gas Emissions

Greenhouse gases (GHGs) are a group of compounds that have a high transmittance of most electromagnetic wavelengths of solar radiation but low transmittance of infrared (heat) radiation. The earth is continuously heated by solar radiation from the sun and is cooled by emitting infrared radiation to the sky. When higher levels of GHGs are present in the atmosphere, more of the radiation being emitted by the earth is reflected back to the earth's surface rather than escaping into space, while solar radiation is still able to penetrate the atmosphere. By trapping energy within the earth's atmosphere, GHGs contribute to global climate change. GHGs include water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), ozone (O_3), nitrous oxide (N_2O), and chlorofluorocarbons (CFC). Carbon dioxide is emitted as a byproduct of the combustion of fossil fuels (coal, natural gas, petroleum). The majority of GHG emissions from human activities are in the form of CO_2; 81 percent of the net global GHG emissions in 2018 were CO_2 (Overview of Greenhouse Gases).

Many regulatory agencies are pursuing electrification (converting natural gas appliances to electric appliances in new and existing construction) as a means of reducing carbon dioxide emissions that result from natural gas combustion. Although electric appliances do not emit greenhouse gases directly, there are indirect emissions associated with the electricity that powers them. The associated emissions depend on the makeup and operation of the portfolio of power generation facilities of a particular electric grid (such as renewables, versus nuclear, versus fossil-fuel based generation).

Electric grids are comprised of four main components: the generators that produce the electricity, the transmission lines that carry the high voltage electricity over long distances, the distribution network that transmits the electricity from the transmission lines to homes and buildings, and the loads that draw power from the electric grid. The generators are the main component responsible for GHG emissions; however, the efficiency of the energy distribution infrastructure also plays a role in emission rates. On one end of the spectrum, if the electricity powering an electric load is produced by renewable sources (solar, wind, hydroelectric, etc.) the indirect GHG emissions rate is zero. On the other end of the spectrum, if coal fired power plants are used to generate electricity to power an electric load, the indirect GHG emissions rate is two to three times higher than the direct emissions rates of modern natural gas burning power plants. Most electric grids have a diverse portfolio of power generation assets including some mixture of renewables, natural gas, and coal. The deployment of these assets varies depending on availability and demand.

Embodied emissions from production of construction materials and equipment, and emissions from construction activities are not considered in this study and are an area of potential future work.

Marginal Green House Gas Emissions Factors

This study used the 2022 TDV long run marginal emissions factors including CH_4_leaks_with 20-year global warming potential (GWP) factors (Version ID: Long Run Marginal Emissions Factors CH4_Leak_20yr_15RA) (Energy and Environmental Economics, Inc., May 2020). The long run marginal emissions factors assume that annual electricity sector emissions limits corresponding to the PATHWAYS scenario 80x50 emissions reduction are met through supply side renewable procurement and incremental renewables are brought online to offset emissions impacts of new loads.

Construction Cost Estimation

A combination of cost data from several sources was used to estimate the cost of each potential upgrade measure. The cost data sources include Skanska, a construction and cost estimation firm (Skanska, 2019), RS Means construction cost databases (Gordian Group, 2019), and publicly available sources including the Database for Energy-Efficient Resources data accessed through the Remote Ex-Ante Database Interface and CalETRM with associated library of utility energy efficiency program workpapers (California Public Utilities Commission, 2021), incremental cost studies from California (Itron, 2014) and the Northeast Energy

Efficiency Partnerships (Navigant, 2015), as well as reports for Codes and Standards Enhancement (Energy Solutions, September 2020). These cost data sources were used to find cost information on equipment materials cost, installation cost, and overhead and profit costs to determine the total cost of each upgrade.

Energy costs were estimated using California's TDV method, which is relevant to building code compliance for builders and the representative utility rate schedules which are relevant to building occupants or operators who will pay those operating costs. In this way the incremental first cost for construction of the buildings to reach ZNE based on TDV was the primary optimization criteria with the net present value of the construction and operating costs as a secondary optimization criterion.

This comprehensive modelling and cost calculation strategy allows cost comparisons that include both primary effects as well as the interactions between measures. Considering interactions between measures is critical to capture how upgrades in efficiency in some systems can lead to reductions in size and cost of other systems. For example, efficiency upgrades in lighting or building envelope can reduce the heating and cooling loads, reducing the size and cost of the HVAC and solar power systems.

Need for Optimization

By combining construction cost estimates for each measure with hourly full year building performance simulation and hourly TDV factors the TDV cost-effectiveness of each combination of interacting measures for each of the building types in each of the California climate zones were determined. The result is building- and climate-specific cost-optimized technology packages for achieving as close to ZNE-TDV as TDV cost-effectively possible.

Previous Work

Technical Feasibility of ZNE

In 2012, a study was conducted by several of the California utilities *The Technical Feasibility of Zero Net Energy Buildings in California*. That report assessed the potential performance of top-of-the-line residential and commercial buildings that would be constructed in 2020 to see how close they could come to meeting the CEC's ZNE goals. In that study, 12 different Department of Energy (DOE) building prototypes were update ed with an integrated package of efficiency measures and on-site renewable energy systems to come as close as is reasonably possible to zero net energy. The 12 DOE building types in that study can be found in Table 1.

Table 1: Building Types Analyzed in the 2012 ZNE Feasibility Report

Feasibility Report: Building Types	
Single Family Residential	Secondary School
Low-Rise Multifamily Residential	Large Hotel
High-Rise Multifamily Residential (HRMF)	Grocery
Medium Office	Full-service Restaurant
Large Office	Hospital
Strip Mall	Warehouse

Source: ARUP, *Technical Feasibility of Zero Net Energy Buildings in California*

All the building prototypes were simulated for a full year of weather data in seven representative California climate zones. The central finding was that ZNE buildings would be technically feasible for the majority of California's new construction market in 2020. The only two building types that could not reach ZNE were large hotels and hospitals.

When improving the design of the DOE prototypes to approach ZNE, the research team on that project implemented energy saving parameters in a specific order of design focus. First, the energy efficiency of the building was improved as far as technically feasible and then the remainder of the buildings' energy consumption was offset using solar PV panels. The capacity of the solar PV panels was limited by the available roof area. The specific order of the design focus is listed in Table 2.

Table 2: Order of the 2012 ZNE Feasibility Report Implemented Improvements to Baseline Models

2012 ZNE Feasibility Report: Design Focus			
1	Reduce Loads	4	Energy Recovery
2	Passive Systems	5	On-Site Renewables
3	Active Efficiency	6	Cogeneration

Source: ARUP, *Technical Feasibility of Zero Net Energy Buildings in California*

There were some notable assumptions made in that report that could have influenced its findings. These assumptions are:

- Electricity exports from the photovoltaic panels to the grid were considered equivalent to electricity imports. Both the imported and the exported electricity were valued using California's TDV method. TDV was designed to account for the production and distribution costs of energy imports; there are potential costs associated with exporting electricity to the grid that are not accounted for in the ARUP feasibility report.
- The ARUP report assumed that overproduction from the photovoltaic panels could be traded to offset natural gas consumption. This allowed natural gas to be used by the building while still obtaining the goal of zero net energy. However, most California utilities do not allow electricity exports to offset the cost of natural gas in this way.

- Another main assumption in the ARUP report was that 80 percent of the non-skylight roof area was available for solar power. If the energy needs were not met by the rooftop photovoltaics, the parking lot area was used. The average parking lot size for each building was determined using aerial imagery of parking lots in Berkeley, Fresno, and San Diego; it was assumed that 35 percent of the parking lot area was available for PV panels.
- The building shape from the DOE prototypes were not altered. This implies architectural features that can have significant energy savings were excluded in the ARUP analysis.

The ARUP study focused on assessing the technical feasibility of reaching zero-net-energy but did not account for the cost effectiveness of the improvements made to the prototypes. In other words, the costs of the implemented energy savings measures were not considered when making the design decisions for the building. In the feasibility report, it was recommended that further research be done that conducts a more thorough cost analysis to ensure that reaching ZNE can be cost effective. The research currently being conducted by the WCEC is intended to address that recommendation.

This previous work only looked at the technical feasibility of achieving ZNE without any consideration for the potential increased cost of the ZNE buildings.

Cost-Effectiveness of ZNE Buildings

Since the inception of this study one other team comprised of Lawrence Berkeley National Laboratory, E3, and Frontier Energy has completed a smaller scope optimization of cost-effectiveness of ZNE residential buildings in California (Wei, 2021). This study defined ZNE on a TDV 2022 basis, considered lifecycle costs to the building developer and owner from construction and utility bills, covered single family homes in California’s CZ 16 and low-rise multifamily buildings in three climate zones, and considered battery systems with different control strategies as well as building pre-cooling controls strategies. The overall conclusions were that a range of ZNE-TDV designs can achieve lower customer lifecycle costs for all-electric and mixed-fuel cases in all climate zones studied, but generally with higher initial costs, that cost-effectiveness is dependent on utility tariff structures, and that lower cost batteries with tariff or grid responsive controls can enable cost-effective ZNE-TDV. (Wei, 2021)

Several other reports and resources cover ZNE new construction cost-effectiveness primarily concluding that ZNE can be achieved at similar or moderately higher cost than code compliant buildings. Each report and resource consider different segments of the buildings market including commercial buildings, single family residential, low rise multifamily residential, and high rise multifamily residential. Each of these resources chooses a definition for ZNE, what costs to consider, and what savings to consider if any. Most of these resources use the site energy definition of ZNE where on-site renewables produce enough energy to offset the annual energy consumption of the building without consideration of the times that energy is consumed or generated. Most of these resources consider costs to the building developer and owner in terms of additional construction cost that is then offset or partially offset by utility bill savings. Multiple reports and articles discuss the general trends where efficiency upgrades costs are included in long term financing so that utility bill savings fully pay the additional financing costs or mortgage bills (Sullivan, 2019). Many resources discuss ZNE new construction enabling factors including: the decreasing costs of PV systems (Davis Energy Group, 2012), greater use of energy modeling software tools (Davis Energy Group, 2012;

Lesniewski, 2013), growing pool of design professionals with relevant skills (Davis Energy Group, 2012), and cost "containment" strategies including design-build or integrated project management (Lesniewski, 2013). A collection of related resources and reports for efficient building design is maintained by the New Buildings Institute (New Buildings Institute, 2022).

Table 3 shows the selected previous work chosen for the literature review. The New Buildings Institute (NBI) develops guides for building developers and designers based on aggregated and summarized cost-benefit assessments of multifamily residential buildings (New Buildings Institute, 2017) and broadly general guidance on the process of gathering the building development and design team, project management, and what technologies to consider (New Buildings Institute, 2018). The general recommendations in these guides help building designers to select technologies of interest but are not cost optimizations for zero net energy buildings. The team worked with NBI to understand the depth of these previous analyses and selected NBI's recommendation to use Skanska to provide pre-construction cost estimates for upgrades.

Table 3: Selected Previous Work Literature Review Summary

Study Author (Institution(s))	Design Optimization	Building Types	# of CA Climate Zones	ZNE definition	Costs considered	PV	Batteries	Controls Optimization
Wei, 2021 (LBNL, E3, Frontier)	Yes	Residential SF, LRMF	SF 16 LRMF 3	TDV 2022	Construction + Utility Bills	Yes	Yes	Precooling, Battery
Davis Energy Group 2012	No	Residential, Commercial	NA	Site	Construction	Yes		
New Buildings Institute 2017	No	Residential Multifamily	No CA CZ	NA	Construction	No	No	No
Sheridan, 2018 (Urban Land Institute)	No	Commercial, MF	NA	Site	Construction	Yes		
Sullivan, 2019 (Zero Net Energy Project)	No	Residential, Commercial	NA	Site	Construction + Utility Bills	Yes	No	
TRC, 2019	No	Commercial	16	NA	Construction + Utility Bills + TDV	Yes	Yes	No

Source: University of California, Davis

Reach Codes Cost-Effectiveness

As part of Title 24 building code development, the cost effectiveness of different potential efficiency upgrades is considered. Because the building code is a minimum code with prescriptive and or performance requirements the upgrades considered tend to be small incremental changes that are cost-effective across a range of building types and climate zones. In addition to the minimum code the California investor-owned utilities (IOUs) hire consultants such as TRC and Energy Soft to develop reach codes with higher energy efficiency requirements that localities can adopt if they are cost-effective and result in lower energy consumption than Title 24 (TRC, 2019). The cost-effectiveness analysis for reach codes covers several different types of technologies in a range of building types but analyses are typically done in parts over several years covering a small number of technologies and building types in each report.

The broader *2019 Nonresidential New Construction Reach Code Cost Effectiveness Study* used methods and approaches that are slightly different than those used in this study and come to very similar conclusions including: there are opportunities for cost-effective efficiency upgrades for all building types in most climate zones, the building type and climate zone have a significant influence on cost-effectiveness, for all-electric buildings cost savings from eliminating natural gas infrastructure can make them more likely to be cost-effective, lighting upgrades have large total energy savings (TRC, 2019). This study advances to competitive optimization of upgrades required to understand the lowest cost pathways to ZNE-TDV whereas reach code studies typically pick packages of measures and allow negative and low-cost measures to subsidize other measures that would not be more cost-effective than PV or battery systems so are not a lowest cost optimization.

Recently interests have evolved to include zero-net carbon buildings and grid-interactive efficient buildings that are beyond the scope of this current study but are areas of interest for future work.

CHAPTER 2: Project Approach

The approach for this project is to use EnergyPlus models and simulation automation strategies that include cost models for each energy saving measure. The resulting parametric analysis are used to identify an integrated package of energy saving technologies and on-site renewable energy generation or battery energy storage that allow the associated building type to reach ZNE in the most cost-effective way possible.

Modeling

To reach this project's objective, parametric energy analyses were performed on multiple building types in each of California's 16 climate zones. Each parametric analysis attempts to identify an integrated package of energy saving technologies and on-site renewable energy or dispatchable energy storage resources that allows the associated building type to reach ZNE in the most cost-effective way possible. There are more than 10,000 potentially unique combinations of technologies and renewable energy or energy storage sources that will allow each building type to reach as close to ZNE as is cost-effectively possible in each of the 16 climate zones.

Building Prototypes

The building types that this project focused on are commercial and multifamily residential. The specific building end use types were selected because they are predicted to have significant new construction in the coming decade, and they covered the range of common building attributes that are likely to impact the feasibility of reaching ZNE cost-effectively. The types of buildings ranged from single-story low-rise commercial buildings to large multi-story commercial office buildings, as well as high-rise multi-family buildings, which ranged from large roof area to small roof area per square footage or total energy consumption. The types of HVAC systems ranged from central built-up systems to distributed packaged units. The magnitude of internal energy consumption and waste heat generation per square foot ranges from very low to very high. The peak occupancy schedules range from weekday, late evenings to nights and weekends to significant occupancy at all times. Covering these broad ranges of building attributes did a reasonable job of spanning the key parameters affecting the ability to meet ZNE cost-effectively for a wide variety of building types.

The building types chosen for this study represented a baseline of California construction (Table 4). Because this study applied to generalized building use types, the models were based on the most recent version of the DOE EnergyPlus developed by the National Renewable Laboratory (NREL) and the Pacific Northwest National Laboratory (PNNL) that were publicly available (Pacific Northwest National Laboratory, 2018). These building prototypes were modified to meet California Title 24 2019 codes and standards using selected inputs from the Alternative Calculation Manual and CBEC-Com standard building EnergyPlus export files.

Table 4: Building Types Chosen to Represent Baseline Construction in California

Building Type	HVAC Type	Internal Loads	Occupancy Times
High-Rise Multifamily Residential	Central	Low	Always
Large Office	Central	High	Weekday
Stand-Alone Retail	Distributed RTU	Low	Day - Evening
Strip Mall	Distributed RTU	Lowish	Day - Evening
Warehouse	Distributed RTU	Very low	Weekday
Quick-Service Restaurant	Distributed RTU	Very high	Day - Late Evening
Full-Service Restaurant	Distributed RTU	Very high	Day - Late Evening

Source: University of California, Davis

The building models included a level of detail were generalized across buildings of that use type that have typical design, construction, occupancy and use patterns. The prototype models did not contain detailed floor plans and have conceptual HVAC and domestic hot water system designs without detailed design layouts of thermal distribution pipes or ducts. These models were the appropriate level of detail for this broad study but required engineering judgement in selecting appropriate cost and performance inputs and did not consider the full complexities present in a real building.

Modifications for Title 24 Compliance and California Common Practice

All the DOE prototypes models were modified on a case-by-case basis to meet 2019 Title-24 prescriptive energy efficiency code requirements. The models were updated to meet prescriptive code requirements to provide a starting place for efficiency upgrades. No efficiency reductions less than the prescriptive code compliance that could potentially reduce costs were considered. The lowest cost arrangement that met T-24 prescriptive requirements was chosen as the baseline for comparison of upgrades. Efficiency upgrades that led to reductions in the sizing and therefore the total cost of interacting systems was considered.

To meet the Title 24 2019 prescriptive requirements several similar modifications were made to the models of most building types, including:

- Lighting power density.
- Daylighting and occupancy sensors were added to required zones.
- Window U-value and SHGC.
- Wall and roof insulation to meet U-value requirements in each climate zone.
- Elevators (where present).
    - Schedules were modified to match those specified in the 2019 T24 ACM.
    - Lighting power density was adjusted to meet Title-24 requirement .

- Controls were added for exhaust fans and cab lights such that they would shut down automatically after 15 minutes in stationary mode, as required by Title-24.

All the DOE prototype models were modified on a case-by-case basis to match current common construction practices in California. To identify current common construction practices in California several sources were consulted including Skanska (Skanska, 2019), Architects (Woodcox, 2019), building owners and operators (McClendon, 2019), and mechanical systems designers (Cheng, 2021).

In addition, changes were made to the prototypes to facilitate simulation automation and to enable modelling of specific energy savings measures. These changes included:

- Removing original HVAC systems to allow different types of HVAC systems with different efficiency levels to be added parametrically.
- Adding ceiling plenums or drywall cavities to zones.
- Removing existing skylights so that solar tubes could be added to meet daylighting requirements at lower cost.

Buildings were modeled using one orientation for each building type in all climate zones. Estimating the relative cost of different orientations was beyond the scope of this project because it would require detailed site information that is not relevant for generalized building portfolio analysis. This project included seven types of building models.

Large Office

The DOE Large Office building prototype was modified in the following ways to meet the 2019 Title-24 code and match common California building practices:

- An Air-cooled screw chiller with variable speed capabilities for high efficiency was selected as the baseline option for the hydronic cooling loop serving the air handler units.
- Data center power consumption schedule was modified to have a variable power consumption schedule with 30 percent of design power continuous and the remaining 70 percent portion scaled to the office building occupancy with a maximum power draw of 95 percent. This was done assuming that an office building would have a local data center for use by building occupants for security reasons and would otherwise use lower-cost offsite cloud services.
- Supply duct leakage before and after the VAV terminal units was applied at a rate of 7.4 percent each [2022 Title 24, Part 6 Final CASE Report – 2022-NR-HVAC2-F]. Infiltration was assumed to be zero because the building is expected to be pressurized so all leakage will be from inside to outside.
- Replaced recirculating central water heating system with 40 of distributed 50-gallon storage tank or equivalent water heaters placed near where the bathroom or breakroom areas would be in the core zone to eliminate recirculation from a central hot water system. Electric resistance storage tank hot water heater as baseline.

Stand Alone Retail

The DOE Stand Alone Retail building prototype was modified in the following ways to meet the 2019 Title-24 code:

- Heavy Mass Walls to align with tilt up concrete construction and insulation on interior in furred cavities.
- Water heater–One 50-gallon storage tank or equivalent assumed to serve the bathroom for the store. Electric resistance storage tank hot water heater as baseline.

Strip Mall

The DOE Strip Mall prototype was modified in the following ways to meet the 2019 Title-24 code:

- Water heater–One 50-gallon storage tank or equivalent assumed to serve the bathroom for each store. Electric resistance storage tank hot water heater as baseline.

Warehouse

The DOE warehouse model was modified to be compliant with Title 24 2019 prescriptive requirements and to match typical construction practices in California. The most significant modifications were the following:

- The metal frame walls specified in the PNNL models were replaced by tilt-up concrete walls, as is the common practice in California. Fiberglass insulation was attached to the interior surface of the concrete exterior walls, continuously with no thermal bridging.
- The wall separating the fine storage and bulk storage spaces called a demising wall, modeled in the PNNL design as a non-insulated wall, was insulated up to the level required for demising walls under Section 120.7(b)7 of Title 24.
- Use schedules from 2019 Title 24 ACM.
- High efficacy LED high bay light fixtures required to meet code for fine storage area and in the bulk storage was cheaper than metal halide so it was made the baseline.
- HVAC changes from PNNL models–baseline office and fine storage conditioned with RTUs with natural gas fueled furnaces and single speed fans and compressors.
- Light tubes to meet daylighting requirements at the lowest cost.
- Electric resistance water heaters as the lowest cost option.
- The warehouse building is more likely to have flexibility in orientation than other building types. The building was oriented such that the exterior wall of the Bulk Storage faced south to minimize building energy consumption, since that space has a heating setpoint but no cooling setpoint. This rotation maximizes the amount of sunlight the Bulk Storage would receive, while minimizing the cooling load resulting from solar heat gain in the Fine Storage and Office spaces with the office space windows facing north. While more energy may be used for heating in the Office and Fine Storage in winter, winter energy costs and TDV multipliers are lower than their summer equivalents. As such, the orientation described would result in a net benefit for both metrics.

Highrise Multifamily

The DOE highrise multifamily model was modified to be compliant with Title 24 2019 prescriptive requirements and to match typical construction practices in California. The most significant modifications were the following:

- Residential unit space conditioning was changed to four pipe fan coil units served by chiller cooled cold water loop and boiler heated hot water loop.
- Ventilation was changed to balanced ventilation with local exhaust and supply for each zone instead of a central ventilation system to align with current design practice. The

local systems do not have cost effective ventilation air precooling options and have reduced benefits from duct sealing so those were not considered.

Full-Service Restaurant
The DOE Full-Service Restaurant prototype was modified to meet the 2019 Title-24 code:

- For simplicity, all outdoor air was routed through the roof top package units and in climate zones where it was necessary the minimum air flow rate was increased until unmet hours were satisfactory.

Quick Service Restaurant
The DOE Quick Service Restaurant prototype was modified in the following ways to meet the 2019 Title-24 code:

- For simplicity, all outdoor air was routed through the roof top package units and in climate zones where it was necessary the minimum air flow rate was increased until unmet hours were satisfactory.

Time Dependent Valuation

EnergyPlus full year simulations produce hourly electrical and natural gas energy consumption outputs that were post-processed to be multiplied by the 2022 hourly 30-year TDV factors for the respective climate zone to calculate the annual total TDV kBtu and then multiplied by the $0.154/kBtu conversion factor to calculate the 30-year non-residential net present value of societal cost for the energy consumption pattern of that building (Energy and Environmental Economics, Inc., May 2020).

Utility Tariffs

The net present value of 30 years of utility bill savings added to the additional cost of upgrades was calculated for the most TDV cost-effective package of measures including either solar or battery systems for each building type in each climate zone to reach or approach ZNE-TDV. The utility bill analysis takes the EnergyPlus full year simulations hourly electrical and natural gas energy consumption outputs and considers over 50 investor-owned utility rate tariffs available to a building and selects the eligible lowest cost option for the baseline and the lowest cost option for the selected measure package in each location. The tariff eligibility consideration includes building location for IOU service territory and rules regarding peak demand, PV, and battery energy storage. EnergyPlus full year simulations produce hourly electrical and natural gas energy consumption outputs that were post-processed to be multiplied by the correct hourly tariff energy and demand costs as well as fixed charges to calculate the annual total utility bill. The utility bill annual savings were calculated by subtracting the selected measure package annual utility bill from the baseline lowest cost title 24 compliant building annual utility bill. The net present value (NPV) of the utility bill annual savings was calculated assuming that the tariff rate structure remains constant over the 30-year study period and uses a discount rate of 5 percent (3 percent real plus 2 percent inflation) to be consistent with TDV method (Energy and Environmental Economics, Inc., May 2020). The additional construction cost for the selected package of measures is calculated by subtracting the baseline lowest cost title 24 compliant building cost from the selected measure package building cost including interactions between measures that reduce or increase the cost of interacting systems such as HVAC sizing. The utility bill savings cost-effectiveness metric for the selected measure package is defined as the 30-year NPV of utility bill savings plus the additional construction cost for that package of measures.

In cases where battery systems increase the demand power (kW) above the demand eligibility for the largest demand commercial tariff, this study assumes that the largest demand commercial tariff is used. Investigation of the eligibility rules and interconnections costs for larger demand systems were beyond the scope of this project.

Greenhouse Gas Emissions Reduction Cost-Effectiveness

The cost per metric ton (1,000 kg) of carbon dioxide equivalent emissions reduction was calculated for the most TDV cost-effective package of measures for each building type in each climate zone. The annual GHG emissions were calculated by multiplying the EnergyPlus hourly electrical and natural gas energy consumption outputs by the greenhouse gas carbon dioxide equivalent hourly long run marginal emissions factors including CH_4 leaks with 20-year global warming potential (GWP) factors developed with the 2022 TDV factors (Version ID: Long Run Marginal Emissions Factors CH4_Leak_20yr_15RA) [2022 TDV Methodology Report]. These long run marginal emissions factors assume that annual electricity sector emissions limits corresponding to the PATHWAYS scenario 80x50 emissions reduction are met through supply side renewable procurement and incremental renewables are brought online to offset emissions impacts of new loads. The total marginal emissions results for the selected measure package with photovoltaics and with batteries were subtracted from the results for the baseline lowest-cost Title-24-compliant building to calculate the annual carbon dioxide equivalent emissions reduction. The additional construction cost for the selected package of measures is calculated by subtracting the building cost for the baseline lowest-cost Title-24-compliant building from construction cost for the selected measure package, including interactions between measures that reduce or increase the cost of interacting systems, such as HVAC sizing. The GHG emissions reduction cost effectiveness metric of $/tonne CO2e reduction was defined as the additional construction cost for the selected measure package, divided by the measure package 30-year GHG emissions reduction. The selected measure package 30-year GHG emissions reduction was calculated by multiplying the annual GHG emissions reduction for the selected ZNE-TDV measure package by 30.

For measure packages that reach or approach ZNE using PV systems, the PV lifetime is assumed to be 25 years to match the panel-output warranty period. The 2021 NREL Annual Technology Baseline cost projections were used to estimate replacement costs for the PV system at the 2047 replacement year and the residual value of the PV systems at the 2052 end of study year (National Renewable Energy Laboratory, 2022) with the net present value determines using a 5 percent discount rate (3 percent real plus 2 percent inflation) to be consistent with TDV methodology (Energy and Environmental Economics, Inc., May 2020).

For measure packages that reach or approach ZNE using battery energy storage systems, the battery lifetime is calculated based on the manufacturer-specified cycle life of 8,000 cycles combined for each climate zone depending on the number of TDV optimum charge and discharge cycles per year. The 2021 NREL Annual Technology Baseline cost projections were used to estimate replacement costs for the PV system at the climate zone specific replacement year(s) and the residual value of the battery systems at the 2052 end of study year (National Renewable Energy Laboratory, 2022) with the net present value determined using a 5 percent discount rate (3 percent real plus 2 percent inflation) to be consistent with TDV method

(Energy and Environmental Economics, Inc., May 2020). Because the TDV factor value time series fluctuations differ between climate zones, the number of charge discharge cycles per year varies between climate zones giving the battery system lifetimes in Table 5.

Table 5: Battery Lifetime by Climate Zone

Climate Zone	Cycles per Year	Battery Lifetime (years)
1	539	14.8
2	543	14.7
3	526	15.2
4	512	15.6
5	595	13.4
6	650	12.3
7	521	15.3
8	607	13.2
9	516	15.5
10	666	12.0
11	672	11.9
12	643	12.4
13	498	16.1
14	749	10.7
15	501	16.0
16	485	16.5

Source: University of California, Davis

This method of calculating cost effectiveness of GHG reduction is somewhat speculative and could be improved by using detailed lifetime and detailed projected replacement cost data for each measure. However, because the efficiency measures contribute a fraction of the TDV reduction and of the increased construction costs this large additional effort was deemed to be beyond the scope of this study.

Simulation Automation

EnergyPlus input IDF files are generated for different combinations of building type, climate zone, and upgrade technologies. The different technologies were added to the simulation through measures, which take as input the objects currently in the model and parameters for the technology being added. The first step in creating a measure was manually modifying one simple IDF file with the IDF editor to get a template of what the measure should do. This was used to make a list of what objects the measure must add. Within the measure code, most objects were added to the model using their text format representation in an IDF file. This was done to make going from a handmade IDF file with the added technology to code automatically adding the technology to a model almost as easy as copy-paste. The text of the IDF objects were added directly to the IDF file.

Other objects added to the model were almost entirely specified except for a few fields, which were usually related to the input parameters for the technology. An example was a new type of insulation material added to the model to replace existing insulation. Adding these objects was almost as easy as copy-paste, with parameter values inserted into the string representing the IDF object in the appropriate fields.

In contrast, some object types were too highly dependent on existing objects in the model to use a simple copy-paste with a few fields changed. An example of this was the Branch and BranchList objects for specifying air loops for all the conditioned Zone objects. These were added with more complex code to find all conditioned zones in the model, creating branches for all the equipment for each zone, and correctly connecting the equipment together into the desired loop.

Lastly, objects in the original IDF are modified by some measures. An example of which was changing the Construction for "BuildingSurface:Detailed" objects in the model to use a different insulation material. This was easily done by finding the array representing the "BuildingSurface:Detailed" object's fields, and changing the text of the field specifying the surface's Construction object.

All these IDF files were combined into an EnergyPlus group file, which iteratively runs all the simulations.The large number of simulations required to model all combinations of energy savings measures across all building types and climate zones would lead to prohibitively long EnergyPlus simulation times. To reduce total simulation time building simulations were first performed for each individual energy savings measure and the results were post-processed to find the individual energy savings measures that achieve cost-effective TDV reductions in any climate zone. These cost-effective energy savings measures were then simulated in all combinations in all climate zones for a particular building type. Cost-effectiveness was measured by TDV $ reduction divided by the increased building construction cost which iwas effectively a TDV return on investment (TDV $/$). An individual energy savings measure was considered cost-effective in a climate zone and building type if it saves more TDV $ per increased building construction cost (TDV $/$) than PV or Batteries, respectively, can achieve in that climate zone and building type.

After all combinations of cost-effective energy savings measures for a building type were simulated in all climate zones the results were post-processed to find the package of energy savings measures that achieved or most closely approached ZNE-TDV in combination with either PV or in combination with battery energy storage. This means that the entire package of energy savings measures including PV or battery systems will be more cost-effective than adding PV or battery systems to the baseline building configuration. Investments in additional construction costs were prioritized for the most cost-effective TDV savings measures and PV or battery systems to find the cost optimum path to achieve or approach ZNE-TDV for each building type in each climate zone.

Cost Data and Common Construction Practices: Heating, Ventilation, and Air-Conditioning Thermal Distribution Types

The primary source of cost data was Skanska USA Building Project Planning Services a pre-construction cost estimation group. Skanska is a multi-national design and construction firm that has built many very high-efficiency and early ZNE buildings. They have also developed a large database of real costs for high efficiency equipment that is not available from other cost data sources. Additional sources were used to augment this cost data including manufacturer provided cost information, California Investor Owned Utility white papers approved by the CPUC for use in Deemed efficiency measures as part of the READI database (California Public Utilities Commission, 2021), and RS Means (Gordian Group, 2019).

Roof Top Packaged Units (RTU)

Roof top packaged units (RTUs) are by far the most common HVAC system type for single story and small multi-story commercial buildings (Table 6). The most typical arrangement of RTUs is to have one RTU serve each thermal zone in a building called single zone. RTUs use vapor compression equipment to provide cooling and for heating can use either integrated natural gas fueled furnaces or use the vapor compression system in reverse as a heat pump. Baseline RTUs were assumed to meet the minimum code required efficiency and have single speed supply fans with static pressure and fan total efficiency determined using the DOE methodology developed by NREL for the original reference models (National Renewable Energy Laboratory, February 2011).

Upgrades to the baseline RTUs were selected based on cost effectiveness market adoption estimates from Skanska (Skanska, 2019). Standard EnergyPlus performance curves were used matching the number of speeds for the supply fan and the compressor. For upgrade from gas furnace heating to heat pump, the heat pump cooling and heating COP was assumed to be the same and the vapor compression system was designed to meet the larger of hourly average heating or cooling loads. Table 7 shows supply fan Pressure and efficiency values used in this study.

Table 6: RTU Characteristics

RTU Characteristics	Baseline	Good	Better
COP (Cooling and for heat pumps Heating)	3.34	3.85	4.11
Gas furnace thermal efficiency	0.82	0.82	0.82
Supply Fan Speeds	Single	Continuously Variable	Continuously Variable
Economizer	Yes	Yes	Yes
Compressor Speeds	Single	Single	Continuously Variable

Source: University of California, Davis

Table 7: Supply Fan Pressure and Efficiency Inputs

Source: National Renewable Energy Laboratory, U.S. Department of Energy Commercial Reference Building Models of the National Building Stock, 2011

Variable Air Volume System

Large commercial buildings, such as the Large Office and Large Hotel building types, often use variable air volume thermal distributions systems to condition zones and in California climates typically use hydronic VAV terminal unit reheat to supply all heating needs, so this study chose these system architectures (personal communication Gwelen Paliaga TRC). This study baseline heating and cooling source equipment was an air-cooled high efficiency variable speed screw chiller and conventional boiler with variable speed hydronic pumps. Head pressure and total pump efficiency were based on the DOE Prototype models (PNNL reference).

System Type	Pressure Rise		Fan Mechanical Efficiency	Total Fan Efficiency**	Nominal Motor Efficiency
	in. w.c.	Pa			
Exhaust fans*	0.5	125	(a)	0.338	(a)
Unit heaters	0.2	50	0.650	0.536	0.825
PTAC and FCU fans	1.33	330	0.650	0.520	0.800
CAV < 7,487 cfm	2.5	622	0.650	(b)	(c)
CAV ≥ 7,487 cfm, < 20,000 cfm	4.46	1110	0.650	(b)	(c)
CAV ≥ 20,000 cfm	4.09	1,018	0.650	(b)	(c)
VAV < 4,648 cfm	4.0	995	0.650	(b)	(c)
VAV ≥ 4,648 cfm, < 20,000 cfm	6.32	1572	0.650	(b)	(c)
VAV ≥ 20,000 cfm	5.58	1388	0.650	(b)	(c)

The selection of the baseline chiller was based on recent results from the DOE Green Proving Ground that found that variable speed air cooled screw chillers could achieve similar efficiency as water cooled centrifugal chillers (Powell, 2019) and that air-cooled screw chillers were less custom design and therefore had more generalizable efficiency and cost (Day, 2019). The maximum size of the considered screw chiller type was 350 tons, so models used multiple units of this type with associated COP and $/ton installed costs scaled proportionally to meet cooling load. This chiller selection is speculative due to lack of information of current new construction practices with regards to the specification of detailed chiller features and types.

Condensing Boiler or Air to Water Heat Pump

This study considered VAV reheat heat source upgrades to a condensing boiler or heat pump (Table 8). The condensing boiler equipment selected to match cost data had a rated thermal efficiency of 95.7 percent at nominal thermal power, supply water temperature, and delta T. The heat pump equipment selected to match cost data had a rated COP of 3.12 at the nominal thermal power, and the study selected supply water temperature and delta T. The efficiency of these upgrade options in the whole building simulations depends on a large number of variables including the equipment controls setpoints, VAV terminal unit heating coil performance, water loop piping head pressure, hot water pump flow rates and total efficiency, water temperature reset strategies, and building zone temperature controls setpoints. The supply water temperature and delta T inputs were determined based on a recent study of heat pump efficiency and personal communication with building design engineers at Taylor Engineering (Feng, 2018; Cheng, 2021). Head pressure and pump total efficiency and controls settings inputs from the DOE prototype models (Pacific Northwest National Laboratory, 2018) were used with continuously variable hot water pump speed controls for all variations.

Table 8: VAV Hot Water Reheat Setpoints

	Rated Efficiency at selected setpoints	Supply water temperature (LWT ^{o}F)	Supply water delta T (LWT-EWT ^{o}F)
Conventional Boiler	84% thermal efficiency	160	40
Condensing Boiler	95.7% thermal efficiency	140	30
Heat Pump	3.12 COP	115	13

Source: University of California, Davis

Hot water piping and VAV terminal unit heating coil sizing and cost remained fixed independent of load reductions or increases from measures so that consistent cost data could be used. Potential future work could include developing detailed VAV reheat system designs to enable investigation of the controls options, tradeoffs between construction cost and energy consumption for different heating coil and hot water distribution piping.

Hydronic Fan Coil Units

An alternative to moving larger volumes of supply air to heat and cool spaces is to only move as much air as is required for ventilation and to heat and cool spaces using fans that blow air from the spaces over hydronic coils. This study considered 4-pipe fan coil units that are served by hot water and chilled water pipes. All fan coil unit fan controls were continuously variable speed with fan total efficiency and static pressure determined using the DOE methodology developed by NREL for the original reference models (National Renewable Energy Laboratory, February 2011). FCU cost remained fixed independent of load reductions or increases from measures so that consistent cost data could be used. These fan coil units were served by the chiller, boiler, condensing boiler, and heat pump options discussed in the previous section.

Future work could expand the cost data and level of detail of the HVAC system design to enable variations in fan coil sizing to be considered.

Ducts and Duct Insulation

For buildings with central heating and cooling equipment using air distribution in long duct systems the duct and duct insulation costs were normalized by the maximum design day air flow rate in cubic feet per minute (cfm) to determine the $/cfm. Efficiency measures that reduced the cooling or heating loads and therefore reduced the total air flow rate were credited with reduced construction costs by enabling duct downsizing with this $/cfm factor. Buildings where changes in duct costs were considered include: Large Office, Large Hotel (public spaces).

Dedicated Outdoor Air System (DOAS)

Dedicated Outdoor Air Systems (DOAS) condition outdoor air for ventilation using vapor compression systems similar to those in RTUs. DOAS systems were considered in the Small Hotel and Large Hotel building types serving the residential rooms. These DOAS systems were assumed to have single speed fans with fan total efficiency and static pressure at rated flow rate determined using the DOE method developed by NREL for the original reference models (National Renewable Energy Laboratory, February 2011).

Energy Savings Measures Considered

Based on the technology review, the following technologies were modeled to create cost-optimized technology packages for zero-net-energy commercial and multi-family residential buildings in California.

- Photovoltaic Systems
- Battery Energy Storage Systems
- LED Lighting Lamps and Fixtures
- Linear Fluorescent Lamps
- Compact Fluorescent Lamps
- Screw Based LED Lighting
- High Intensity Discharge Lamps
- Advanced Lighting Controls
- Indirect Evaporative Cooling Ventilation Air Pre-Cooling
- Air Duct Sealing
- Additional Exterior Wall or Roof Insulation
- Aerosol Envelope Sealing (Infiltration Reduction)
- Domestic Hot Water Heating with
    - Electric Storage tank
    - Gas Storage Tank

- Window Coatings, Argon Fill, and Frame Thermal Breaks
- Light Tubes / Skylights
- Exterior Wall Window Overhangs
- Interior Window Light Shelves
- Window Blinds / Shades
- Variable Air Volume System Reheat Equipment
    - Gas Condensing Storage Tank
    - Gas Tank-less
    - Heat Pump Water Heaters
- Efficient Elevators
- Higher Solar Reflective Cool Roof
- Added Thermal Mass from Concrete or Phase Change Material

Photovoltaic (PV) System

Photovoltaic (PV) solar collectors convert solar radiation into electricity and are the most commonly used form of on-site renewable energy generation for buildings. The conversion efficiency of PV panels is improving steadily, and costs are declining steadily. At the time of data collection in 2019 a common standard PV panel efficiency was 19.5 percent, with common mid-level panel efficiency of 20.3 percent and premium panel efficiency of 21.4 percent for monocrystalline panels with efficiency averaged over the whole fabricated dimension of the panel including the frame. Inverters were assumed to have a constant efficiency of 97.5 percent based on SMA inverter product specifications CEC efficiency rating.

Careful design of roof access and other roof top mounted equipment was assumed to enable PV panels to use 80 percent of roof area (Arup North America Ltd., 2012).

For buildings that have sufficient roof area to reach ZNE-TDV with energy saving measures and roof mounted PV, spaced rows of optimally tilted panels of the standard efficiency are the most cost-effective PV system type. For buildings that do not have sufficient roof area to reach ZNE-TDV with energy saving measures and roof mounted PV arranged in spaced rows of optimally tilted panels, horizontal racking (flat) orientation panels have a higher energy production per roof area and are still cost-effective on a TDV $/$ basis so flat panel mounting was used. For the restaurant building type the PV panels were assumed to be at the optimum angle on the 80 percent available area of the south facing half of the sloped roof.

Premium efficiency panels were found to be less cost-effective (TDV$/$) than the standard efficiency panels so they were not considered further. Parking lot canopy racking can increase the area available for PV systems, but canopy racking increases costs. Parking lot canopy PV systems were still cost effective with a TDV$/$ greater than one in all climate zones. Single story buildings without energy intensive cooking loads can reach ZNE-TDV with more cost-effective rooftop PV systems. The large buildings that do not reach ZNE TDV are more likely to be built in urban areas where land costs are significant and parking structures are more common than open air parking lots. For this reason, only rooftop PV systems were considered.

For buildings that have insufficient roof area to reach ZNE-TDV when combined with all efficiency upgrades that are cost effective on a TDV cost per additional construction cost basis, the fraction of total T24 compliant baseline TDV reduced is reported for the selected package of efficiency and PV measures.

The real completed construction project photovoltaic system installed cost data including overhead and profit were provided by Skanska and are from 2019 and relevant for REC N Peak

2, 325W, 19.5 percent efficiency panels and SMA Sunny Tripower Core 1 commercial system inverters with 97.5 percent CEC efficiency (REC, 2019; SMA, 2019). These 2019 cost data, shown in Table 9, were adjusted for recent historical and projected price reductions to a 2022 construction date using the normalized price reduction projections from the NREL 2021 Annual Technology Baseline using median historical cost data for real systems for 2019 and the future cost projections based on the moderate price reduction scenario for commercial building roof mounted PV systems all in 2019 $ (National Renewable Energy Laboratory, 2022).

Table 9: Raw Skanska PV System Installed Costs Including Overhead and Profit (2019 $/W DC at STC)

	Standard (19.5% Efficiency)	Mid-Level (20.3% Efficiency)	Premium (21.4% Efficiency)
Roof mounted (more than 100kW)	$2.95	$3.30	$3.35
Canopy mounted	$5.50	$5.75	$5.90

Source: 2019 Skanska adjusted cost data

The PV panels and inverters were assumed to need replacement after the manufacturer quoted 25-year panel power warranty. Replacement cost estimates assumed that the value of the whole PV system installed cost adjusted for future price reductions using normalized cost projections from the NREL 2021 Annual Technology Baseline for 2047, the year that the system would need to be replaced and discounted these costs to net present value (National Renewable Energy Laboratory, 2022). At the end of the 30-year study period, end of 2052, the remaining PV system life of 20 out of the original 25 years was credited back at the net present value of the projected 2052 value (National Renewable Energy Laboratory, 2022). The net present value of photovoltaic system installed costs including overhead and profit for new construction plus replacement minus end of study period remaining life was $2.03/W DC at STC (2019 $) shown in Table 10.

Table 10: Net Present Value of PV System Installed Costs (2019 $/W DC at STC)

	New Construction	Replacement	End of Study Period Remaining Life Credit
Roof mounted (more than 100kW, Standard 19.5% Efficiency)	$1.92	$0.26	-$0.16

Costs include overhead and profit for new construction plus replacement minus end-of- study period remaining life.

Source: Skanska cost estimates from previously completed construction.

A sensitivity check showed that the shading from PV panels on the roof did not significantly impact the total annual TDV or cost-effectiveness of PV systems or efficiency measures. For this reason, the team decided to neglect roof shading from PV panels to eliminate the significant extra time to re-simulate buildings and iterate to find the precise small reduction in PV sizing to reach ZNE-TDV.

The team made a number of simplifying assumptions with these secondary effects not considered: panel shading (from nearby buildings, trees, or roof top equipment), panel layouts that increase the energy produced per roof area at higher cost per energy produced, panel temperature coefficients for power production reduction, lifetime panel power degradation, panel dirt accumulation, assumed no inverter clipping as would occur if inverter sizing was less than peak panel power output. Future work could consider cost-benefit tradeoffs of roof top canopy racking to lift PV panels above other rooftop equipment to enable higher roof area coverage or single axis tracking systems for PV panels in large arrays to increase total PV energy generation in the constrained area.

Battery Energy Storage System

Lithium-ion batteries have seen rapid price reductions making them one of the most cost-effective energy storage technologies. Battery system costs were based on a lithium iron phosphate chemistry with an inverter power capacity equal to the total battery energy storage capacity in a turnkey system including balance of systems installation. A charging and discharging control optimization algorithm was developed to maximize the TDV savings of the battery system. Because TDV factors are developed on an hourly basis this battery with matching power and energy capacity will maximize the net TDV savings by completely discharging at the highest TDV factor hour(s) each day with perfect information about all 8,760 hourly TDV factors. The lowest TDV factor hour each day has a very similar magnitude to other hours during the day. This study spread charging over the three lowest TDV factor hours for each battery charge discharge cycle so that the battery driven increase in utility demand charges can be reduced with negligible loss in TDV savings. Each climate zone has different TDV factor shapes, and the battery control can charge and discharge multiple times in a day to achieve the maximum TDV benefit. The TDV benefit and electricity utility costs include a round trip efficiency of 93 percent from inverter and battery losses. The battery round trip efficiency and energy storage capacity are assumed to be constant over the battery life.

In a real building there will not be perfect information about future TDV factors and marginal emissions. For this reason, the TDV and emissions savings from the perfect information case was multiplied by a factor of 0.65 to discount for imperfect information based on personal communication estimation of the impact of imperfect information on battery utility cost savings from battery control optimization researcher Dr. Tu Nguyen (Nguyen D. T., 2020; Nguyen T. A., 2017). This 0.65 savings derating factor is somewhat speculative and would change if TDV factors and marginal emissions are more or less predictable.

Although somewhat speculative, the study allowed any battery size and allowed battery discharge power export to the grid to illustrate the technical and economic potential of the battery systems when allowed to function in ways that maximize the TDV benefits to society. No existing utility tariffs were found that allowed batteries to charge from the grid and to discharge at a rate that results in net export of energy back to the grid. Although clearly speculative, the commercial utility tariff was applied with the corresponding peak demand eligibility to buildings with battery packages. For large buildings the baseline building can be near the largest peak demand covered in commercial tariffs and when adding battery systems resulted in above peak demand that was covered by any commercial tariff the commercial tariff with the highest demand eligibility was used. Potential future work includes exploring industrial tariffs to cover these cases.

Construction cost data were based on the costs to a real completed project using a Blue Planet Energy Blue Ion LXHV turnkey system including inverters, electrical connections, safety systems, other balance of system components, installation, overhead and profit. This battery system uses Lithium Ferrous Phosphate battery chemistry, is islanding capable, has 100 percent useable capacity, 8,000 cycle life to 70 percent of initial capacity for 100 percent depth of discharge cycles, with a 15-year warranty (Delta, 2020; Blue Planet Energy, 2020). The basis of this cost estimation is Skanska 2019 adjusted cost data for a 125kW 128kWh system with a cost of $580.77/kWh. Battery system costs per power (kW) and energy storage capacity (kWh) decline with increasing battery system size. Cost estimates for each part of the turnkey battery system from Skanska were adjusted to estimate costs for different sized systems. The battery system capacity required to reach ZNE-TDV for each building type, climate zone, and selected package of efficiency measures resulted in an energy storage capacity range of 80kWh to 25MWh with cost range from $600 to $508 per kWh. Above a battery capacity of 425kWh the cost was set to be constant $/kW to reflect multiple modular systems due to expected space constraints.

The actual completed construction project battery cost data provided by Skanska are from 2019 and were adjusted for recent price reductions to a 2022 construction date using the normalized price reduction projections from the NREL 2021 Annual Technology Baseline for commercial battery systems with 1-hr storage for equal power (kW) and energy storage capacity (kWh) (National Renewable Energy Laboratory, 2022; Cole, June 2020). The batteries and power electronics were assumed to need replacement after the manufacturer quoted 8000 charge-discharge cycles. Because the hourly TDV factor value fluctuations differ between climate zones the number of TDV optimum control strategy charge-discharge cycles per year varies between climate zones giving the battery system lifetime in Table 11. Replacement cost estimates assumed that 75 percent of the value of the whole battery system installed cost predicted by the NREL 2021 Annual Technology Baseline for the year that the system needed to be replaced in each climate zone (National Renewable Energy Laboratory, 2022; Cole, June 2020). The net present value of these year of replacement projected costs were then calculated to match the year that replacements were needed in each climate zone. At the end of the 30-year study period, end of 2052, the small remaining battery life was credited back at the net present value of the projected 2052 value per kWh (National Renewable Energy Laboratory, 2022; Cole, June 2020).

A cost adder was applied to the battery systems for the space they take up inside the building of $39.58/kWh based on an average California construction cost of $475 per square foot (Paliaga, 2019) and the footprint of the Blue Ion battery system (Blue Planet Energy, 2020).

Table 11: TDV Optimum Battery Control Cycles per Year

Climate Zone	Cycles per Year	Battery Life (years)	Net Present Value adjusted 2022 cost and replacement cost modifier (2019 $)
1	539	14.8	1.11
2	543	14.7	1.11
3	526	15.2	1.05
4	512	15.6	1.04
5	595	13.4	1.13
6	650	12.3	1.15
7	521	15.3	1.05
8	607	13.2	1.14
9	516	15.5	1.04
10	666	12.0	1.15
11	672	11.9	1.15
12	643	12.4	1.14
13	498	16.1	1.03
14	749	10.7	1.16
15	501	16.0	1.03
16	485	16.5	1.02

Table includes lifetime, and net present value cost for construction, replacements(s), and end-of-life value.

Source: University of California, Davis

The duration of battery charging has a significant impact on the building electrical power demand and on the utility bill demand charges and utility tariff eligibility rules. This study spread battery charging over three hours and discharging over one hour.

For this broad study the following secondary effects were not considered: no battery capacity degradation, no battery self-discharge, constant round trip efficiency over lifetime, no battery system cooling energy consumption, no optimization for charging more than three hours.

In potential future work the control algorithm optimization code could be used to compare battery control optimized for TDV savings to battery control optimized to maximize utility bill savings or greenhouse gas emissions savings. Other potential future work refinements include consideration of: thermal energy storage technologies that compete with batteries, outdoor battery systems, flow batteries, and other types of energy storage technologies.

Lighting and Fenestration Technologies

Lighting Fixtures and Lamps

Starting with the zone use types from the DOE EnergyPlus prototype models (Pacific Northwest National Laboratory, 2018), EPRI and University of California Davis (UCDavis)'s Western Cooling Efficiency Center (or WCEC) consolidated a list of technologies per application with associated wattages per lamp, fixture consumption, lumens per lamp, fixture delivered lumens, and lifetime lumen output degradation, among other specifications. The list provided baseline, more energy efficient, and most energy efficient options per bulb/fixture type. This list was compiled using data from existing and past EPRI research projects, literature review, and online search results for up-to-date products. A sample of the list covering some options for troffer lighting is shown in Table 12.

Table 12: Example Broad Category Troffer Lighting Options

Technology	Lifespan	Wattage Per Lamp/Fixture	Total Fixture Consumption (W)	Approx. Lumens /Lamp	Approx. Lamp Efficacy	Typical CRI Range	Typical CCT Range (K)	Approx. Lumens / Range
Fluorescent Tubes -25W	25,000	25	110	2050	82	75-90	3000-8000	5740
Fluorescent Tubes -28W	25,000	28	125	2296	82	75-90	3000-8000	6429
LED Tubes- Type A- Plug in	50,000	12	52	1440	120	80-95	2400-6000	5184
LED Tubes – Type B- Direct AC	50,000	12	48	1440	120	80-95	2400-6000	5184
LED Tubes – Type C – LED Driver and Tube Replacement	50,000	12	48	1440	120	80-95	2400-6000	5184
LED Troffer	65,000	45	45	4500	100	80-95	2400-6000	4050

Source: EPRI Martin Prado

To verify the compiled numbers, a search was done per fixture type using the Design Lights Consortium (DLC) database. The DLC is a non-profit organization which provides lighting specifications for energy efficient products. Its database is well established and lists more than 540,000 lighting products. Each search provided thousands of results which were then sorted and analyzed to determine average lighting values per fixture type. The average efficacy was used to determine the typical energy efficiency of each fixture type, which could be considered the "better" option out of three: "good," "better," "best." For clarity, the calculated averages and other numbers were not used as the strict numbers for the final assumptions but were used as a cross-checking against the EPRI compiled list to ensure due diligence in the evolving lighting market. Cross-checking EPRI's list against the database, each technology and their associated performance values was verified with a high level of confidence. Secondary research was performed to determine the typical type of lighting fixture used in each building zone such as troffers in office buildings, or recessed downlighting/screw in lamps for hotel rooms. These associations were confirmed via conversations with Skanska (Skanska, 2019).

Lighting Sizing

For the cost analysis, the estimated number and type of fixtures per building zone was needed. To determine how many fixtures were needed per zone, typical lux (lumens/m^2) values were aggregated from the IESNA Lighting Handbook (Illuminating Engineering Society, 2011), Lighting Design Lab (Lighting Design Lab, 2020), and CEC Title 24 documentation. Typical lux values vary between 100-500 lux depending on zone usage type. Areas with a need for high lighting levels (such as kitchens, and retail) command lux values closer to 500. Areas with less need (like dining, warehouses, and storage,) have lower typical lighting levels of 100 or 200 lux.

To determine the number of fixtures per area, a coverage area per fixture was assumed based on source lumens output, a light degradation ratio of 70 percent (to be sized to provide sufficient illumination at the end of lamp/fixture life) (Royer, 2014), and a useful lumens delivered ratio of 70-100 percent depending on source and fixture type. Fixtures that report measured fixture lumens delivered have a useful lumens ratio of 100 percent such as fixtures with integrated LED sources. Fixtures with LED lamps use a 90 percent useful lumens ratio as the light is typically more directed than non-LED bulbs. Fixtures with replaceable lamps (linear fluorescent or compact fluorescent) use a fixture useful lumens ratio of 70 percent (Pacific Northwest National Laboratory, 2009) or a fixture specific ratio from manufacturer specifications. To find the number of fixtures required in each zone the total area of each zone was multiplied by the typical illumination lux for that zone usage type to calculate the total lumens required and this result was divided by the lumen delivered output per fixture to calculate an estimated number of fixtures per zone and per building. The total wattage of all fixtures combined in the building was then divided by the total building area to ensure that the allowed Title 24 watts per square foot threshold per building was not crossed. Any fixture configurations that resulted in an unallowable watts per square foot were discarded which eliminated incandescent options.

For buildings with multiple fixture types, an assumed utilization ratio was applied. For instance, in hotel rooms, recessed downlighting and screw-in bulbs were calculated separately to meet 100 percent of the lighting level load (150 lux). However, it was assumed that 50 percent of the lighting level is met by recessed downlighting and that the other 50 percent is met by screw-in bulbs. Including both at 100 percent would have provided 300 lux to the area, so to account for this, the number of recessed and screw in bulbs were cut in half to meet the 150-lux recommendation for this space type. In retail applications, the number of troffers specified provide 100 percent of ambient lighting and an additional 20 percent of the area requires task lighting to highlight certain areas.

For troffers and high bay lighting fixtures using integrated LED light sources, it was assumed that lumen management was used to dim the lights at the beginning of their life to avoid over lighting and reduce energy consumption. The 70 percent lumen degradation assumption means that at beginning of life these fixtures would use 70 percent of their rated full illumination power and at end of life they would use 100 percent of the full illumination power to provide the required space illumination. The simulations use an average of beginning and end of life power at 85 percent of rated full illumination power as an estimate of the average power consumption over the study period.

Based on the number of fixtures required and total cost per fixture it was found that fixtures with higher lumen output resulted in lower total cost. The final lighting products were selected from available products to match cost data and the particular products were selected to provide the maximum lumen output expected to provide acceptable evenness of illumination across the spaces (Table 13). For troffers there is an unfair advantage for the linear fluorescents because there are high output products available that can deliver twice the number of lumens and therefore have half the number of fixtures and associated installations costs compared to the integrated LED products.

Table 13: Specifications and Cost of Selected Lighting Fixtures and Lamps

Selected Lighting Fixtures and Lamps	Fixture Wattage	Fixture Useful Lumens Ratio	Initial Fixture Lumens	Fixture LPW	Lumen Management Average Wattage (85%)	Materials Cost ($/fixture)	Installation Cost ($/fixture)
Troffers - 4 of Fluorescent Tubes Lithonia 32W 2GT8 R80 HO LL (BF 0.88)	112.6	0.7	10912	96.88	NA	$121.32	$80
Troffers - LED Troffer Lithonia 2GTL4 5000LM LP840	38.8	1	5062	130.50	32.97	$116.14	$80
Troffers - Reach 2021 LED Troffer Illumisoft Ecowing E W-V-24-48-36W-XX-55L-CT50-D-120	36.0	1	5500	152.78	30.60	$170.00	$80
Recessed Downlighting - 32W CFL Flood (120w equiv) Lithonia LP6FN	32.0	0.5106	1225.4	38.29	NA	$73.00	$80
Recessed Downlighting - 22W LED (120W equiv) Juno IC22LED	15.6	1	1400	89.74	NA	$97.00	$80
Screw in Lamps - 27W CFL (100W equiv) Philips 458273	27.0	0.7	1850	68.52	NA	$7.50	$6
Screw in Lamps - 18W LED (100W equiv) Cree A21	17.0	0.7	1600	94.12	NA	$10.00	$6
Bay Lighting - 400W HID - MH Lithonia THD 400MP A15 TB SCWA LPI (BF 0.88)	454.5	0.803	36000	79.20	NA	$260.00	$240
Bay Lighting - LED (575W equiv) Lithonia JEBL 50L 50k 80CRI WH	218.0	1	31815	145.94	185.30	$300.00	$240
Bay Lighting - LED (400W equiv) Lithonia JEBL 24L 50K 80CRI WH	181.6	1	26890	148.07	154.36	$217.56	$240

Source: University of California, Davis

Lighting Controls

Due to high variability in actual energy reduction from different control devices, a single confident percent energy reduction from controls could not be found. Original estimates placed savings of between 5-80 percent, a range that does little to provide meaningful modeling results. Further secondary research was conducted to analyze existing case studies regarding different control products (occupancy sensors, networked controls, localized/IoT controls). These case studies were taken from various sources including the Lighting Design Lab, UC Davis California Lighting Technology Center, EPRI, E3, and other established entities. The case studies were used to reduce the expected reduction range (5-80 percent) to feasible, incremental savings. Based on the findings, a conservative estimate of energy savings was established for occupancy, vacancy, and cloud-based controls.

Savings Determination

Based on the case studies and secondary research performed, two buckets of energy saving were decided upon for lighting controls:

1. Baseline of occupancy + photocells (where applicable).
2. Energy efficiency upgrade to cloud based and IoT connected controls systems which integrates local controls, with a larger occupancy, vacancy, and daylighting sensors.

Occupancy and/or photocells are required by T24 in most areas and were therefore decided as the baseline option with a bucket of 30 percent savings decided upon when upgrading from "No controls" to a code compliant combination of occupancy and photocells. Thirty percent is conservative within the range of 5-80 percent expected reduction, but based on the case studies collected, is a realistic percent reduction. The second bucket looks at a connected, IoT approach to controls, which integrates occupancy, daylighting sensors, and localized system level controls. These savings were estimated at 60 percent for a connected control system based on the sources listed in Table 14. IoT lighting controls upgrades tended to see between 50-70 percent overall reduction in energy use across building types, therefore a 60 percent blanket savings was used for all buildings.

Table 14: Lighting Controls Case Study Energy Savings

Building Type	Technology	Savings	Source
All	Localized/IoT	47%	lightingcontrolsassociation.org
All	Localized/IoT	Variable	products.currentbyge.com
All	Localized/IoT	50-70%	e3tnw.org
		25-50%	
		25-70%	
		50-60%	
All	Localized/IoT	Up to 49%	buildings.com
All	Localized/IoT	70%	products.gecurrent.com
All	Advanced Lighting Control System (ALCS)	50-70%	e3tnw.org

Source: EPRI Martin Prado

Exterior Overhangs and Interior Light Shelves

Inputs for the models are based on the addition of exterior wall window overhangs. Overhangs were considered for west and a combination of south and west windows because they result in the largest TDV savings and TDV return on investment. For buildings with windows on only one face and where that face is oriented to the south overhangs were simulated for the south facing windows. The benefits of overhangs and light shelves are significantly lower for north or east facing windows. An overhang design tool was used to determine the appropriate depths and heights of the window exterior overhangs based on latitude and size of the windows (Sustainable By Design, 2008). The overhang depth was chosen as 2.5 feet out from the wall at the top of the window. Multiplying the width of the overhang (assumed to be the width of the window) by the depth of the overhang calculated a total area of southern wall window overhang per applicable zone. Zones that do not include southern or west facing windows or would not commonly have a southern window overhang were excluded from the calculation. A materials cost of $120 and installation labor cost of $80 per square foot of installed window overhang was estimated by Skanska and applied to the total areas to estimate cost of implementation.

Placing exterior overhangs below the top of the window and adding an interior light shelf can project daylight deeper into the building. An energy savings calculator from overhang manufacturer Kawneer was used to select which south facing building zones were deep enough to get energy savings from the light shelves (Kawneer, 2020).

No attempt was made to generate a detailed design with optimum overhang depth or placement so real systems with optimal design may be slightly more cost-effective than predicted in this study. This study also did not consider the potential for increased thermal bridging due to external overhang mounting hardware and this would be expected to slightly reduce cost-effectiveness.

Shades and Blinds

Energy impacts from shades and blinds are strongly dependent on how occupants use them, and both the energy performance and costs are highly variable. For these reasons a set of previously modeled shades and blinds were selected from EnergyPlusV9-3-0\DataSets\WindowBlindMaterials.idf for blinds and EnergyPlusV9-3-0\DataSets\WindowShadeMaterials.idf for shades for this work. This EnergyPlus object uses a schedule that assumes that occupants will lower the shades or blinds when solar irradiance on the window is high. This schedule is a near optimum schedule for energy savings in cooling dominated climates where shades are likely to be most valuable and for that reason it is expected to overestimate the energy savings compared to less consistent real occupant usage. This study assumed the baseline had no shades or blinds because they are not required by Title 24, so the full cost of shades or blinds is carried as the upgrade cost. If the baseline case included shades or blinds, then the costs to upgrade to better energy performance options would be significantly smaller. Overall, this study may underestimate cost-effectiveness for shades and blinds.

Windows

Conversations with Skanska determined window types and framing material are commonly used in commercial and multifamily building types. For instance, for storefront windows, storefront/curtainwall windows with aluminum framing were specified as the commonly implemented type and frame.

Based on the window types covered in the modeling (fixed, operable, curtainwall/storefront), the National Fenestration Rating Council (NFRC) fenestration directory was consulted to determine common U-factor, SHGC, and VT values for the different window types (National Fenestration Rating Council). The NFRC is a non-profit organization which provides customers with energy performance ratings for most fenestration products, and its directory lists all available certified products. Refining the directory search by window types identified manufacturers with products that meet the description of the search. As an example, for a curtain wall system, 41 manufacturers are identified within the directory. Across different manufacturers, the U-factor, SHGC, and VT values remained relatively consistent across products with similar specifications. For instance, a double paned, Low-E, argon-filled curtainwall has similar values from one manufacturer to another. The list of manufacturers was narrowed down per each fenestration type based on the number of products available (assuming a high number of products means the company is well established in the market). The reduced list of manufacturers was vetted using a quick online search to ensure the company was well established for each specific product.

Figure 2 shows the window double pane surface elements. After two to three manufacturers were chosen to represent each window type, the list of available products (typically in the 100s at this point) was compared against Title 24 thresholds to vet out any products that do not meet Title 24 requirements. For instance, curtainwalls for commercial applications must meet or exceed the following specifications:

U-factor <= 0.41

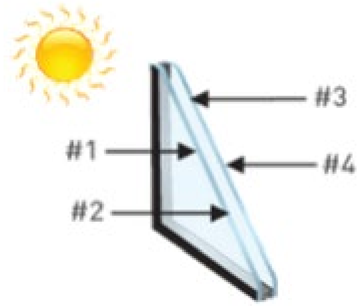
SHGC <= 0.26

VT >= 0.46

Any products that do not meet the T24 requirements were thrown out, leaving behind a condensed list of products with varying values and varying properties. To further narrow down the options, tinted windows were also discarded as the tints have a significant impact on performance values but are varied from site to site within the same building type.

Of the remaining products, four were chosen to represent the group for a baseline, ECM 1, ECM 2, ECM 3 scenarios. Skanska was consulted to provide typical installed cost for the specific products with values closest to the T24 threshold and typical upgrade options including coatings, fill, and frame thermal break. Table 15 shows the variation of values moving from baseline to ECM1, ECM2, and ECM 3. The numbers next to the Low-E values dictate on which window surface the coating has been applied. For ECM1 and ECM3, two low-E coatings were applied to improve performance.

Figure 2: Window Double Pane Surface Identification



Identification numbers for each surface of a double paned window

Source: *CEC Title 24 Documentation*

Table 15: Window Baseline and Upgrade Specifications

	Description	**Summer U-factor (Btu/h·ft2·F)**	**Winter U-factor (Btu/h·ft2·F)**	**SHGC [Fraction]**	**Visible Transmittance [Fraction]**
Baseline	1" Double pane VNE1-53 triple silver Low E coating on surface #2, argon fill, and VG 451 non-thermal frame	0.34	0.3	0.18	0.43
ECM1	1" double pane VNE1-53 Substrate on surface #2, with argon fill, VG 451 non-theal frame and Room side low-e coating on surface #4	0.31	0.27	0.21	0.45
ECM2	1" double pane VNE1-53 Substrate on surface#2, with argon fill and VG 451T thermal frame	0.3	0.26	0.22	0.47
ECM3	1' double pane VNE1-53 on surface #2, with argon fill, VG 451T thermal frame and Room side low-e on surface #4	0.26	0.22	0.21	0.45

Source: University of California, Davis

Although an involved process, a high confidence in available and commonly used fenestration products and performance values was achieved. To determine costs of upgrading to more efficient products.

The energy savings associated with window upgrades depends on the orientation of the windows. This study considered upgrades of all windows on the building together as one measure. The orientation of a real building is constrained by the site and building usage so that it is often not a flexible variable. For building types with windows on only one face, the cost-effectiveness of window upgrades may depend on the arbitrary building orientation. The window upgrades selected as the most typical that had reliable cost data decrease U-value and slightly increase the solar heat gain coefficient. In heating dominated climate zones with north facing windows both performance changes are valuable so that the window upgrades are more likely to be part of the optimum package. In cooling dominated and mild climates and where windows do not face north the increase in solar heat gain coefficient reduces the benefits of the decrease in U-value and the window upgrades are less likely to be selected. Feedback from architects suggested that building types with windows on multiple faces may not accept the different visual aesthetics of different window types on different faces. Potential future work could include analysis of different window properties on each of the building faces.

Skylights and Light Tubes

The specifications for skylights and light tubes were established via the same means as the windows, filtering results from the National Fenestration Rating Council. The number of products for skylights and light tubes were much fewer than windows, distinguishing two major brands (Wasco Products Inc. and VELUX Co.) as having a large presence within the database. Assuming fixed skylights and using the Title 24 values (U-factor, SHGC, and VT) as the threshold, the list was narrowed down to the following values. Skanska was consulted to provide typical installed cost for the specific products with values closest to the T24 threshold including coatings, fill, number of glazing layers and glazing gap summarized in Table 16.

Table 16: Skylight and Light Tube Specifications

Skylights	**U-factor**	**SHGC**	**VT**	**Improvement**
Good	0.56	0.25	0.56	Low-e, air
Light tubes	**U-factor**	**SHGC**	**VT**	**Improvement**
Good	0.51	0.23	0.51	Baseline – 3 glazing layers
Better	0.38	0.23	0.51	4 glazing layers
Best	0.18	0.22	0.53	5 glazing layers

Source: University of California, Davis

Sizing and Placement

The number of skylights per building zone was determined using Title 24 guidelines. Building zones were chosen based on the appropriateness of skylights. These areas are typically larger than 5,000 ft^2 with minimum ceiling heights of 15 ft. Based on these guidelines, as well as looking at zones specified in the DOE prototype models to have skylights, a list of building zones was established to be appropriate for skylights or light tubes.

For each zone, the area covered by skylights was reduced based on the requirement of a minimum 75 percent of floor area covered by daylight. Any area with windows was then further reduced by considering the area with lighting needs met by the windows. For instance, the large stores in the stripmall began with a total area of 3750 ft^2. This was reduced to 2812.5 ft^2 based on the 75 percent requirement and then further reduced to 2331 ft^2 since 481 ft^2 of floor area was met by the large storefront windows.

Assuming 4'x6' skylights and three different sizes of light tubes, the amount of floor area covered by each type was calculated using the Title 24 definition of skylit daylit zone, in which a skylit daylit zone is any area directly under the skylight or any area within 0.7 times the ceiling height from the edge of the skylight in all directions. This does **not** consider any internal obstructions to the natural light as determining a percentage of light obstructed varies on a project-by-project basis requiring much more specific building design details than available for this study. The calculated number of skylights and light tubes are shown in Table 17.

Table 17: Skylight and Light Tube Dimensions and Numbers Required

SUMMARY		# of skylights (4'x6') needed	# of Light tubes needed	Size of light tube
School	Gym_ZN_1_FLR_1 ZN	14	15	14"
Stand Alone Retail	Core_Retail ZN	38	19	21"
Stripmall	Lgstore	16	10	21"
Stripmall	Smstore	31	19	21"
Warehouse	Zone2 Fine Storage ZN	21	7	29"
Warehouse	Zone3 Bulk Storage ZN	57	20	29"

Source: University of California, Davis

In the warehouse building type, light tubes met the Title 24 daylighting requirements at significantly lower cost and upgrades to skylights were expensive and resulted in more heat transfer to and from the outdoors. For these reasons light tubes were considered the baseline option for all building types and skylights are not expected to be cost-effective on a TDV basis.

Upgrades to Heating, Ventilation, and Air-Conditioning Systems

Several different types of upgrades were considered to each of the HVAC system architectures described previously.

Duct Sealing

Sealing ducts can significantly reduce energy waste from leakage of air out of and into ducts and the associated wasted energy usage from fans, heating, and cooling. Sealing of supply ducts was modeled for the Large Office and Large Hotel building types because the energy impacts of leaks from the long length, high pressure VAV distribution system is expected to be higher than for the short, lower pressure duct systems associated with RTUs in most other building types. Baseline leakage rates, sealing effectiveness, and costs were gathered from recent Codes and Standards Enhancement (CASE) Initiative 2022 California Energy Code report on Air Distribution: High Performance Ducts and Fan Systems prepared by Energy Solutions for California Statewide Utility Codes and Standards Team (Energy Solutions, September 2020). The baseline was duct sealing using code required manual methods. The Large Office VAV system will have typical leakage upstream and downstream of the VAV terminal units. Leakage from the high-pressure duct upstream of the VAV terminal units is typically a constant volume flow rate of 7.4 percent of rated flow at design conditions because typical control systems maintain these ducts at a constant pressure regardless of flow. Leakage from the ducts downstream of the VAV terminal units is typically 7.4 percent of the supply air flow rate that changes depending on zone conditions and calls for cooling and heating. Improved manual sealing of ducts can reduce leakage to 3 percent upstream and 3 percent downstream (59.5 percent sealing effectiveness) and these inputs were used as the upgrade case.

Exhaust duct leaks and sealing were not considered in this study but is likely to have a return on investment slightly lower than supply duct sealing.

Duct sealing was not credited with reduced HVAC equipment sizing savings due to issues with EnergyPlus functionality. Future funding could expand this analysis to consider this additional significant cost savings from duct sealing upgrades to further improve duct sealing cost effectiveness.

Air Side Economizer

RTUs and air handler units take in outdoor air through a damper to provide ventilation, typically at the minimum flow rate required by code. An actuated damper called an air side economizer can increase the amount of outdoor air when cooling is required and the outdoor air temperature or enthalpy is less than the return air temperature or enthalpy to reduce cooling energy consumption. Title 24 code requires air economizers for RTUs above 4.5-ton cooling capacity. For RTUs smaller than 4.5-ton cooling capacity, this study assumed that no air economizer was included for baseline so that adding an economizer was considered an efficiency upgrade. Economizers are add-on options sold directly by manufacturers and this study assumed that they did not increase the installation cost and had an additional equipment cost of $500 per RTU (Natural Resources Canada, 2013).

Evaporative Condenser Air Pre-Cooling

Vapor compression cooling systems in RTUs and air-cooled chillers reject heat from refrigerant to outdoor air using condensers (Figure 3). Using evaporation of water to pre-cool the air drawn through the condenser can significantly reduce the air temperature and increase RTU or chiller COP and capacity particularly when outdoor air temperatures are high and when there is low humidity. This project considered evaporative condenser air pre-cooling by adding corrugated type evaporative media upstream of cooling equipment condenser coils because this product type has been found to have high evaporative effectiveness and low power consumption so that they are energy and water efficient in field and laboratory tests by the Western Cooling Efficiency Center of CoilCool products from Seeley and Integrated Comfort Incorporated (UC Davis Western Cooling Efficiency Center, 2015).

The team made a conservatively low estimate of the energy performance by using a value of 0.6 for the wet-bulb effectiveness of the evaporative media pre-cooling air before it was drawn across the condenser based on laboratory and field measurements of real system performance conducted by UC Davis Western Cooling Efficiency Center for Southern California Edison (UC Davis Western Cooling Efficiency Center, 2015; UC Davis Western Cooling Efficiency Center, 2018).

Figure 3: Evaporative Pre-Cooling of Condenser Air for Roof Top Packaged Units (RTU) or Air-Cooled Chillers

Source: Integrated Comfort Incorporated, 2022

The evaporative media adds a small pressure drop that slightly increases condenser air fan power consumption at all times and a small water circulating pump consumes power when pre-cooler is turned on. A conservatively high estimate was made of a decrease in RTU or Chiller COP of 2 percent at all times to account for these small increases in power consumption in a way that allowed simple automation of modelling for this energy savings measure. The 2 percent decrease in COP is based on worst case estimates of the evaporative media pressure drop of 25 Pa from a starting assumption of 50 Pa and used rules of thumb estimates for the fraction of condenser fan power to total RTU or chiller power consumption per ton cooling based on COP from a study by the Florida Solar Energy Center (Parker, 2005).

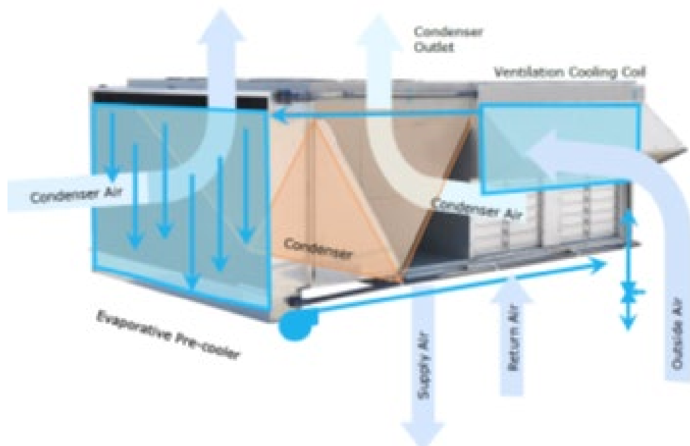
Equipment costs are based on retail pricing shared by Seeley and Integrated Comfort Incorporated. It is becoming more common for cooling equipment manufacturers to offer evaporative condenser air pre-cooling as a factory installed option, so installation costs were assumed to only be considered for provision of the additional water and power as opposed to field retrofit costs. Installation and materials costs for the additional water and power were assumed to add 1/3 of equipment costs. The cost per ton cooling of the RTU or air-cooled chiller declines rapidly with increasing size due to economies of scale. For roof top packaged units, the pre-cooling equipment costs were curve fit to find the $/ton cooling cost based on the capacity of the equipment the pre-coolers were being added to. For large chillers equipment costs were curve fit and extrapolated to 350-ton chiller size to match the air-cooled screw chiller models considered in this study.

Evaporative condenser air pre-cooling energy savings were estimated using conservatively low savings assumptions. Evaporative condenser air pre-cooling costs were not credited with reduced cooling equipment sizing savings due to issues with EnergyPlus functionality. Future funding could expand this analysis to consider this additional significant cost savings from evaporative condenser air pre-cooling upgrades to further improve cost effectiveness. For these reasons the results will give a conservatively low estimate of cost-effectiveness for evaporative condenser air pre-cooling.

Evaporative Condenser Air Pre-Cooling and Ventilation Air Pre-Cooling

Evaporative condenser air pre-cooling inherently cools a sump of water to very close to the wet bulb temperature of the outdoor air. For roof top packaged units that use evaporative condenser air pre-cooling, adding an air to water heat exchanger and water pump enables pre-cooling of ventilation air using this sump water in addition to the condenser air pre-cooling (Figure 4). This add-on leverages the cost of the cooling equipment and condenser air pre-cooler to achieve relatively low-cost cooling of ventilation air. Cost sources and assumptions followed the same methods as evaporative condenser air pre-cooling. The same COP penalty as evaporative condenser air pre-cooling, 2 percent in cooling and heating operation, was used since the additional fan power due to added ventilation air pressure drop was calculated to be negligibly small.

Figure 4: Schematic of Combined Evaporative Condenser Air Pre-Cooling and Ventilation Air Pre-Cooling



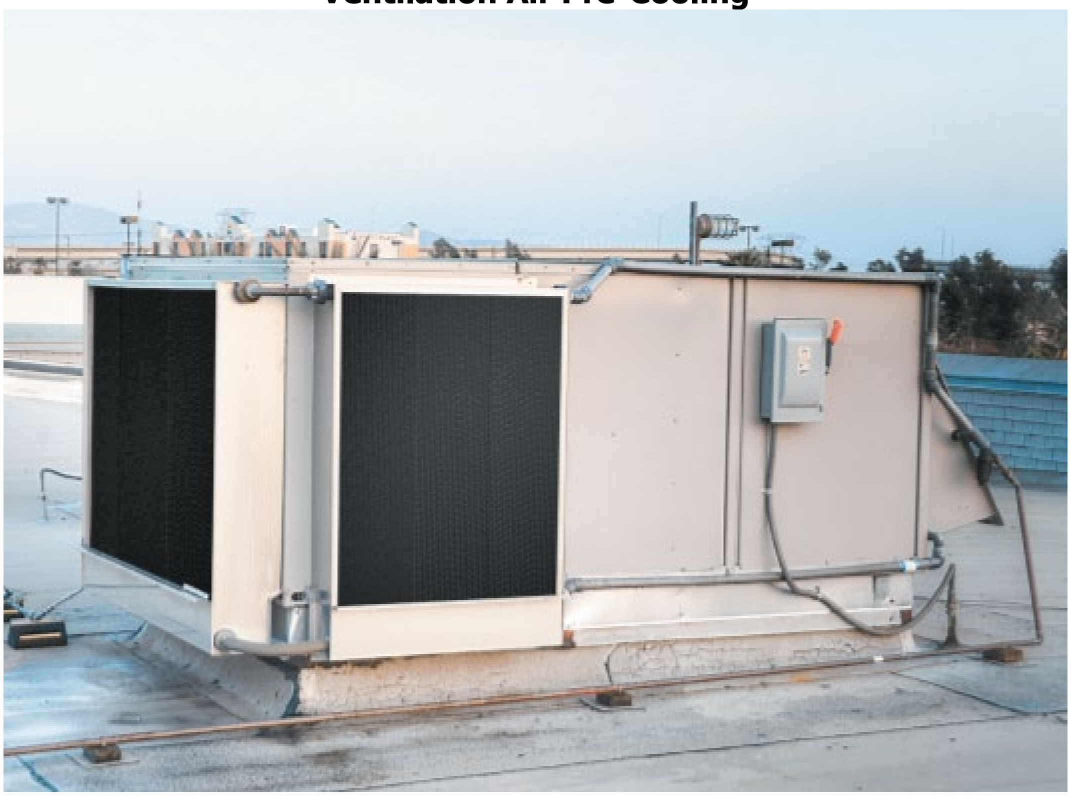
Source: University of California, Davis

For the ventilation air pre-cooling, it was assumed a wetbulb effectiveness of 45 percent for cooling ventilation air based on WCEC field test data of DualCool products from Seeley and Integrated Comfort Incorporated (Woolley, October 2014; Modera, 2015). The measured range of wetbulb effectiveness was 10-55 percent with the high values during hot weather when there is a high wetbulb depression. Selection of an average wetbulb effectiveness value of 33 percent would unfairly penalize the equipment at the times of the highest TDV factors. A slightly higher than average wetbulb effectiveness of 45 percent was selected as a compromise to achieve fair TDV results.

The ventilation air pre-cooling system controls were set to run the condenser fan and indirect evaporative cooling coil whenever the resulting pre-cooled ventilation air resulted in a mixed ventilation and return air temperature above 10^{o}C to avoid overcooling and operation in freezing temperatures. The ventilation air pre-cooling system operates the RTU condenser fan whenever it is operating even if the RTU compressor is not operating. The RTU condenser fan power was estimated as 11 percent of the annual operating average power of the RTU compressor and condenser fan combination based on typical RTU power fractions of 80 percent for compressor, 10 percent for the condenser fan, and 10 percent for the supply fan (OUC Business Energy Advisor, 2019).

Evaporative condenser air pre-cooling with add-on ventilation air pre-cooling (DualCool) was not credited with reduced cooling equipment sizing savings due to issues with EnergyPlus functionality. Future funding could expand this analysis to consider this additional significant cost savings from evaporative condenser air pre-cooling with add-on ventilation air pre-cooling upgrades to further improve cost effectiveness. For these reasons the results will give a conservatively low estimate of cost-effectiveness for combined evaporative condenser air pre-cooling and ventilation air indirect evaporative pre-cooling. Figure 5 shows a real-world example for an RTU With Combined Evaporative Condenser Air Pre-Cooling and Ventilation Air Pre-Cooling.

Figure 5: RTU With Combined Evaporative Condenser Air Pre-Cooling and Ventilation Air Pre-Cooling



RTU with combined evaporative condenser air pre-cooling and ventilation air pre-cooling.

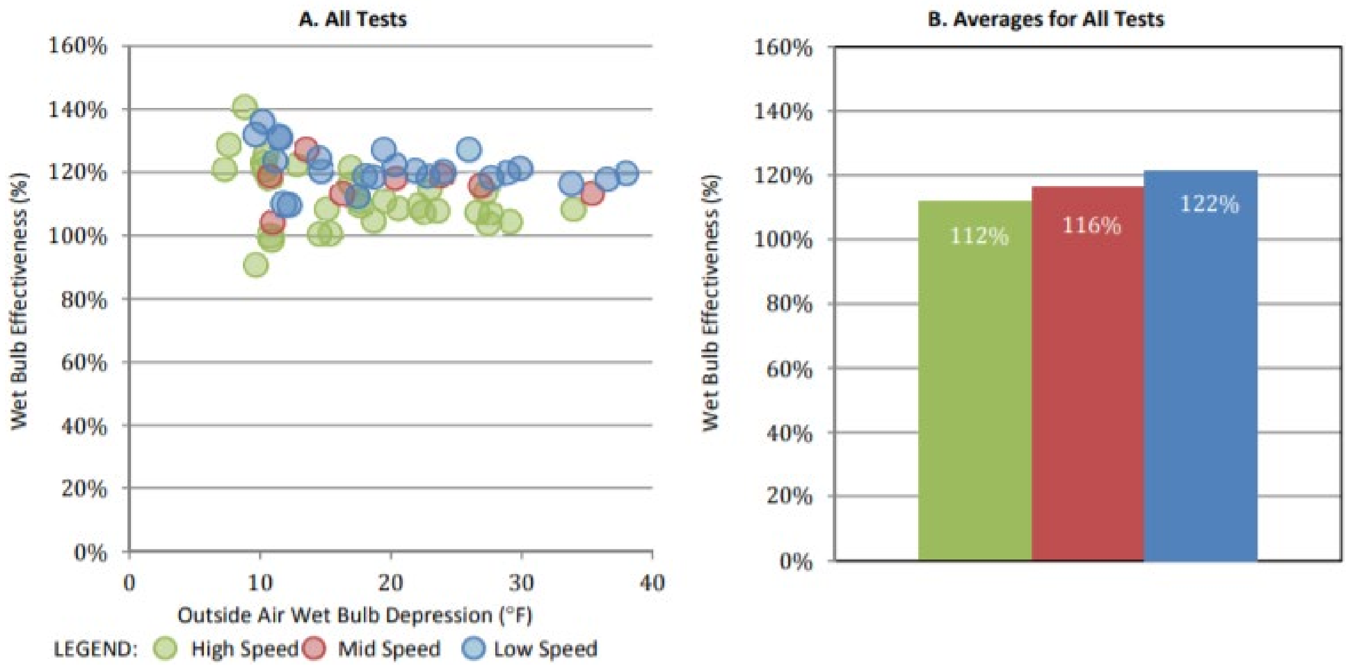
Source: University of California, Davis

Indirect Evaporative Cooling

Indirect Evaporative Cooling (IEC) equipment can cool outside air for ventilation to sub-wetbulb temperatures with very high efficiency without adding humidity. This study arranged IEC ventilation air pre-cooling in parallel with air side economizer(s) so that under normal operation all the ventilation air flow was cooled by the IEC and under economizer operation the same ventilation air flow was cooled by the IEC and the remaining economizer outdoor air flow not cooled by the IEC. This strategy was applied in buildings where all outside air was subsequently cooled by a coil as with large air handler units in the Large Office and Large Hotel serving public spaces and for dedicated outdoor air systems as in the Large Hotel serving residential rooms and Small Hotel.

Modelling used a wetbulb effectiveness of 112 percent based on laboratory tests and field tests of Seeley Climate Wizard equipment and assuming that when used to pre-cool ventilation air that the IEC units run at full speed during all occupied hours or full ventilation hours, Figure 6 (Harrington, 2015).

Figure 6: Field Performance of Indirect Evaporative Cooling



Wet bulb effectiveness as a function of outside air wet bulb depression for three fan speeds (a) results from every test (b) average value for results from all tests

Source: University of California, Davis

IEC fan total efficiency at rated flow rate were determined using the DOE methodology developed by NREL for the original reference models (National Renewable Energy Laboratory, February 2011). IEC fan static pressure rise was estimated from Seeley Climate Wizard electrical power consumption ratings using the fan total efficiency from the DOE method and assuming that the primary air flow was pulled through the unit by the AHU or RTU and the IEC fan pulled secondary air against the return air suction pressure of 1/3 of the AHU or DOAS total fan static pressure rise. The electric power consumption ratings used were for the CW-80 HICAP in the Large Office and Large Hotel and for the CW-80 standard model for the Small Hotel. This method likely overestimates the IEC fan power consumption because the real systems will likely consume less than their rated maximum current draw. IEC controls were set to run the IEC whenever the resulting pre-cooled ventilation air resulted in a mixed ventilation and return air temperature above 15°C to avoid overcooling and operation in freezing temperatures. The IEC equipment cost was estimated by Skanska to be \$3.50 per cfm and installed cost including labor, overhead, and profit was \$5.94 per cfm (Skanska, 2019).

IEC systems were not credited with reduced cooling equipment size reduction savings due to issues with EnergyPlus functionality. Future funding could expand this analysis to consider this additional significant cost savings from IEC upgrades to further improve IEC cost effectiveness.

IEC ventilation air precooling was not considered for ventilation air flow rates under 140,000 cfm due to limitations in cost data. Future funding could gather real completed building construction costs for these smaller IEC applications.

Upgrade Construction Strategies

Cool Roof

A cool roof is a roof that minimizes solar absorption and maximizes thermal emittance. The high solar reflectivity of the roof stops heat from entering the building, and the high thermal emittance gives it the ability to radiate heat out of the material quickly (Department of Energy). Besides reducing the cooling energy by allowing less heat into the conditioned space, these roofs are typically more durable because they are not as quickly deteriorated by the sun. One negative effect of these roofs is that the heating load can be increased in winter months. However, in typical commercial buildings, the savings of cooling energy in summer months is more significant than that lost in winter months by heating. Cool roofs are already in California's Title 24, so this measure selected products that have higher than required reflectivity and emittance.

Thermal Mass

When a larger amount of mass inside the building interior to the envelope insulation is thermally coupled to the interior spaces, then the heating and cooling systems can operate with longer cycle times. For this measure, the total thermal mass was changed by adding an extra one-inch thickness of concrete to slab floors (ground contact or between stories) or to concrete walls if they were interior to the envelope insulation.

This study did not consider the advanced HVAC control strategies that use high thermal mass to shift heating or cooling loads away from high TDV times.

Phase Change Material

Phase change materials (PCM) can provide significant thermal energy storage with less actual material because they change phase and the latent heat associated with this process is large compared to the sensible heat stored in typical thermal mass. This measure placed the PCM above the drop ceiling in the spaces where they exchange heat with return air pulled through the ceiling plenum. The impact of PCMs is strongly dependent on the temperature that they change phase and on the HVAC control system setpoints. This study performed a preliminary assessment of what melt temperature was most beneficial with the typical commercial building temperature setpoints and selected 21C PCM material melt point.

This study did not perform an optimization of PCM melt temperature with different building temperature setpoints because changing the setpoints can negatively impact occupant comfort and requires more specific site and space usage information than was available. This study also did not consider the advanced control strategies that use high thermal mass provide by PCM to load shift heating or cooling away from high TDV times.

Wall and Roof Insulation

Several wall and roof construction assemblies were considered with different insulation materials and thickness options to meet Title 24 requirements in each climate zone (2019 Efficiency Standards, Title 24, 2019). Whole assembly R-value heat transfer resistance values from Title 24 were used to account for thermal bridging effects (Title 24 2019 REFERENCE

APPENDICES / Joint Appendices / Appendix JA4 – U-factor, C-factor, and Thermal Mass Data, 2019). Installed costs including materials, labor, overhead, and profit were estimated by Skanska (Skanska, 2019). For walls, fiberglass batts were the lowest installed cost per material R-value of $0.12 per square foot of wall per material R-value but are typically used in wall cavities where structural elements allow thermal bridging so that the actual increased R-value per additional cost is reduced significantly.

One exception is for tilt-up concrete walls in warehouses where fiberglass batt insulation is attached in a continuous layer to the inside surface of the exterior walls using pins and or adhesive where it was assumed that there was no thermal bridging. For tilt-up concrete heavy mass walls in Standalone Retail stores the insulation is added to the interior surface of the wall with baseline typically one-inch furred studs with fiberglass cavity insulation and gypsum board and upgrades increase the depth of the furred cavity to 3.5 inches as common practice. For walls with studs and flat roofs, the additional insulation with the lowest cost per whole assembly additional R-value heat transfer resistance was continuous foam board insulation (XPS – Extruded polystyrene insulation) with an installed cost of $0.30 per square foot per R-value because there is minimal thermal bridging. Wall construction assemblies were selected from 2x4 16" spacing and 2x6 24" spacing options with fiberglass batt cavity insulation filling the depth of the cavity and exterior XPS foam board continuous insulation in one-inch increments to minimize total installed cost with compliant R-value for baseline and enhanced R-value for upgrades. All buildings have flat roof configurations with built-up roof assemblies and additional XPS foam insulation except the Quick Service and Full-Service Restaurants. The Quick Service and Full-Service Restaurants have sloped roofs with attic spaces and use blown-in fiberglass with an installed cost of $0.08 per square foot per R-value and this study assumed that this additional insulation depth covers the ceiling joists and is, therefore, continuous and has no thermal bridging.

Aerosol Envelope Sealing (Infiltration Reduction)

Building envelopes are notoriously leaky with unintended flows between outside and conditioned spaces and unconditioned spaces that result in additional space heating and cooling energy consumption. While voluntary codes and standards for envelope tightness have existed for decades, only recently have these codes become a requirement. Current manual methods for sealing leaks within a building can fall short of the ultimate tightness goal due to unrecognized leakage pathways, even when diligently applied. The aerosol envelope sealing technology developed by the Western Cooling Efficiency Center (WCEC) at University of California Davis uses an automated method to satisfy the envelope sealing requirement. The process involves briefly pressurizing the building while applying an aerosol sealant "mist" to the building interior. As air escapes the building through leaks in the envelope, the sealant particles are carried to the leaks where they impact and stick, eventually sealing the leaks. A standard blower door is used to pressurize the building for the sealing process and provides real-time feedback and a permanent record of the leak reduction achieved. The technology is thus capable of simultaneously measuring, locating, and sealing leaks in a building remotely.

Baseline buildings of each type use manual sealing infiltration rates specified in the DOE Prototype models. Aerosol sealing can achieve 90 percent reductions in infiltration but depending on when during the construction process it is used new leaks can be made in later stages. This study assumed an 80 percent infiltration reduction from aerosol sealing.

Cost data was supplied by Aeroseal Incorporated that licenses franchise contractors to perform sealing. Costs were adjusted based on national average labor rates for the work crews expected. Economies of scale make sealing lower cost per square foot for larger buildings than for smaller buildings ranging from $1.99 to $0.93 per square foot for the building types in this study.

Other Efficiency Upgrade Measures

Domestic Hot Water Heating

Due to the lack of detailed hot water heating and distribution system design information in the EnergyPlus DOE Prototype models and limitations in cost data this study does not consider upgrades to central domestic water heating systems. This study considered five types of domestic hot water heaters of typical residential size class of approximately 50 gallons storage or equivalent hot water delivery: electric resistance storage tank, natural gas fueled storage tank, high efficiency condensing natural gas fueled storage tank, natural gas fueled tankless, and heat pump. These water heaters were modeled for building types that use one or more of these size water heaters in DOE Prototype models and for buildings like the Large Office that use central water heaters with large recirculation systems that consume excessive amounts of energy to supply relatively little hot water end use. Energy consumption changes and cost differences were simulated for the alternative types. No recirculation systems were considered because energy consumption simulations for systems using demand-controlled recirculation require detailed hot water draw data by location in the building which was not available. Detailed energy efficiency inputs were developed using manufacturer specifications, Energy Star data, and methods developed by the National Renewable Energy Laboratory

Electric resistance storage tank water heaters have lowest installed cost and were therefore selected as the baseline option. The AO Smith ProLine Master HNT-50 was selected as a representative model with installed cost of $875 per unit, 50-gallon (nominal) tank, electric resistance elements delivering 4,500 watts, first hour rating of 62 gallons at a Uniform Energy Factor of 0.92 with a calculated thermal efficiency of 0.98.

Natural gas fueled storage tank water heaters burn natural gas to heat water in a storage tank and have a slightly higher installed cost of $950. The AO Smith Conservationist BT-60 was selected as a comparable model with a 55-gallon (nominal) tank, first hour rating of 83 gallons at an Uniform Energy Factor of 0.62 with a calculated thermal efficiency of 79.8 percent and burner power of 17.6kW. Costs of adding natural gas distribution piping have widely varying estimates but even the lower end of the additional cost estimates were found to reduce the cost effectiveness of this water heater type and make it uncompetitive from a TDV dollar savings per dollar increased construction cost.

Natural gas condensing storage tank water heaters have a significantly higher installed cost of $2,750 compared to the electric resistance version and burns natural gas to heat water in a storage tank. The AO Smith Cyclone Xi was selected as a representative product. Electronic ignition, eliminating the need of a standing pilot flame. Costs of adding natural gas distribution piping have widely varying estimates but even the lower end of the additional cost estimates were found to reduce the cost effectiveness of this water heater type and make it uncompetitive from a TDV dollar savings per dollar increased construction cost.

Natural gas fueled tankless water heaters reduce energy consumption by eliminating tank heat losses and higher efficiency models use condensing heat exchangers for high efficiency. The AO Smith Condensing X3 AT-199X3P was selected as a comparable model with an installed cost of $1,700 per unit, burner power of 199kBTU/hour (58.3 kW) for a maximum hot water delivery rate of 10 gallons per minute, Uniform Energy Factor of 0.93 with a calculated thermal efficiency of 96 percent. Costs of adding natural gas distribution piping have widely varying estimates but even the lower end of the additional cost estimates were found to reduce the cost effectiveness of this water heater type and make it uncompetitive from a TDV dollar savings per dollar increased construction cost.

Heat pump storage tank water heaters use electricity to power a vapor compression system to move thermal energy from the surrounding air to heat hot water in a storage tank. This system was selected as a representative model with installed cost of $1,775 per unit, 50-gallon (nominal) tank, backup electric resistance elements delivering 4,500 watts, first hour rating of 66 gallons at a Uniform Energy Factor of 3.45 with a calculated thermal efficiency of 3.57 and heat pump capacity of 4200 BTU/hr. Where compatible and acceptable, the heat pump water heaters were placed in building zones that required cooling so that the net thermal energy removed from the air minus the tank heat losses resulted in a net reduction in HVAC cooling required.

For storage tank water heaters, a single tank size and standard control strategies were modeled. Future work could investigate strategies to shift loads away from high TDV times by using larger storage tank volumes and or control strategies with timers or that respond to a dynamic TDV signal.

Future work could expand this analysis to central water heaters including condensing boilers and heat pump heat sources, recirculation control strategies, and standard versus compact hot water distribution plumbing designs.

Efficient Elevators

The energy used by elevators typically accounts for 3 to 8 percent of the building’s total electricity consumption. Using the best available elevator technologies, however, can reduce energy use by up to 62 percent (Baggs, 2013). Three notable technologies that are being implemented today are dispatch control software, machine-roomless elevators, and regenerative drives (Sniderman, 2012). Dispatch control software is used to optimize the trips of the elevator to reduce the number of stops the elevator takes and to reduce the waiting time of the passengers. This study did not include dispatch control software due to a lack of detailed data on building occupancy and elevator trips and did not include elevators with no machine rooms because elevator equipment was assumed to be placed in a rooftop space that was unconditioned as in the DOE Prototype models. Regenerative elevator drives capture a portion of the energy that conventional drives typically dissipate as heat into the space surrounding the elevator equipment. This regenerative energy is generated when the system decelerates, and it is fed back into the building’s electricity supply.

This study identified errors in the typical EnergyPlus modelling of elevators that overestimates energy consumption by effectively assuming that all elevator trips are fully loaded due to multiplying the elevator schedule hourly fraction by the maximum rated power of the elevator. To correct this issue this study used energy consumption data from manufacturer Thyssen Krupp and applied a set of multipliers for each elevator baseline and upgrade option in each relevant building type. This study kept the DOE prototype model assumption that elevator equipment was in a roof top enclosure so that waste heat was not transferred to the building. The efficiency upgrades considered were premium efficiency hydraulic fluid for hydraulic elevators in shorter buildings and regenerative drives for traction elevators in taller buildings.

Measures Rejected From Consideration

Several energy saving measures originally targeted for consideration were rejected due to limitations on availability of cost data or energy performance data, limitations in EnergyPlus capabilities to model accurately, or due to requirements for much more detailed site information, building HVAC systems designs, or domestic hot water system designs (Table 19). Estimating the incremental cost of adding or switching between some types of technologies requires more detail about system designs than available in the conceptual EnergyPlus HVAC systems and was time and cost prohibitive to develop for this broad study. Some technologies require unavailable more detailed and probabilistic occupancy information to be accurately modeled including lighting occupancy controls, building energy management systems that reduce heating or cooling in unoccupied spaces, some domestic hot water measures, and demand-controlled ventilation.

Table 19: Measures Rejected from Consideration

Energy Saving Upgrade Rejected	Reason Rejected						
	Limited Cost Data	Limited Energy Performance Data	Limited EnergyPlus capabilities	Requires more detailed HVAC design	Requires more detailed domestic hot water design	Too Expensive unlikely to pay off in California	Requires detailed site or occupancy data
Solar Thermal				x	x	x	
Hybrid PV-Thermal				x	x	x	
Ground Source Heat Pumps						x	x
Chilled Beams				x		x	
Radiant Heating and Cooling				x			
Heat / Energy Recovery Ventilation						x	
Vestibules / Air Curtains		x	x				
Exterior Lighting							x
Higher Cost Insulation (Mineral Wool, Spray Foam, Polyisocyanurate Foam)						x	
Drain Water Heat Recovery					x		x
Upgrades to Central Domestic Hot Water Heating					x		x

Electrochromic Windows	x	x					
Commercial Kitchen Measures	x	x	x	x	x		x
Building Solar Orientation	x						x
Variable Refrigerant Flow (VRF) System			x	x			
Ceiling Fans				x			
Demand Controlled Ventilation				x			x

Source: University of California, Davis

CHAPTER 3: Results

Optimum Measures Selection Method

The package of efficiency measures and PV or battery systems that achieves or most closely approaches ZNE-TDV are selected based on the interacting combined package societal cost TDV$ calculated by adding the positive increase in construction cost above the baseline construction cost to the negative operational TDV$ savings. This societal cost TDV$ is a net present value of first year construction cost increase and 30 years of operational TDV savings. When this value is negative it means that there is a net societal cost savings. In all building types when reaching ZNE-TDV with battery systems this method selects only the efficiency measures that have a greater return on investment TDV$ saved per $ added construction cost than battery systems. In building type and climate zone combinations that can reach ZNE-TDV using rooftop PV this method selects only the efficiency measures that that have a greater return on investment TDV$ saved per $ added construction cost than PV systems. In building type climate zone combinations that cannot reach ZNE-TDV with roof top PV systems this method selects all efficiency measures that have a greater than one return on investment TDV$ saved per $ added construction cost.

After selection of the package based on societal cost TDV$ the results are calculated for the other metrics. The package builder owner cost is calculated by adding the positive increase in construction cost above the baseline construction cost to the net present value of 30 years of negative operational utility bill savings (upgrade + Utility NPV $ change). When the package builder owner's cost is positive that means that there are increased net costs to the builder and the owner or occupants that pay the utility bills. When the most TDV cost-effective package corresponds to large net cost increase to the builder and owner this means that hourly utility rate structures are not well aligned with the societal cost represented by TDV.

The package greenhouse gas emissions reduction cost is calculated as the positive increase in construction cost above the baseline construction cost divided by the 30-year total CO_2e tonne greenhouse gas emissions reduction ($/tonne 30 yr. CO_2e reduction). The package greenhouse gas emissions reduction cost per tonne CO_2e can be compared to other alternative methods for reducing emissions. When the package greenhouse gas emissions reduction cost per tonne CO_2e is high relative to alternative methods for reducing emissions, this means that TDV cost factors are not well aligned with the hourly emissions intensity of grid electricity and natural gas.

How to Use the Technology Recommendations

The selected package of efficiency measures and either PV or battery systems is the most societally cost-effective package of measures as measured by adding the incremental upgrade cost to the TDV $ savings. When the most TDV cost-effective package corresponds to a large net cost increase to the builder and owner this means that policy supports will be needed to encourage adoption of these societally cost-effective options. Policy support can include building codes and regulatory requirements, economic incentives and subsidies, and adjustments to utility tariff structures and grid power import and export rules.

When the most TDV cost-effective package corresponds to high greenhouse gas emissions reduction cost per tonne CO_2e this means that policy support for other emissions reduction options may deserve to be prioritized.

For building designers and builders, the selected efficiency technologies can be prioritized for consideration and modelling for the specific site and building to be built before sizing PV and or battery systems to meet code or achieve other goals.

Recommended Technology Packages by Building Type and Climate Zone

Overall Results

This section discusses the broad trends in results with interpretation and discussion.

Trends in TDV Cost-Effectiveness for PV and Battery Systems

PV and battery systems are societally cost-effective with TDV$/$ greater than one in all climate zones. PV systems achieve a better societal return on investment TDV$/$ than batteries in all climate zones. The differences shown in Table 20 between climate zones are due to interactions of TDV factor hourly shapes and weather patterns in each climate zone.

Table 20: PV and Battery System TDV Cost Effectiveness and Cost of CO_2e Saved

	PV Systems				Battery Systems	
CZ	Tilt Mounted TDV$/$	Tilt Mounted $/30-year tonne CO_2e	Flat Mounted TDV$/$	Flat Mounted $/30-year tonne CO_2e	Adjusted 0.65 TDV$/$	Adjusted 0.65 $/30-year tonne CO_2e
1	2.31	$1,153	2.00	$1,344	1.91	$463
2	3.04	$957	2.70	$1,119	1.75	$465
3	2.94	$915	2.52	$1,098	1.70	$439
4	3.33	$892	2.98	$1,054	1.85	$437
5	3.13	$760	2.67	$951	1.90	$473
6	3.37	$707	2.90	$889	1.64	$491
7	3.01	$721	2.60	$917	2.13	$443
8	3.70	$719	3.25	$900	1.75	$486
9	3.69	$695	3.24	$880	2.33	$435
10	3.58	$687	3.14	$863	1.34	$490
11	3.07	$932	2.71	$1,113	1.52	$485
12	3.09	$968	2.78	$1,111	1.54	$484
13	3.17	$931	2.87	$1,071	2.15	$432
14	3.91	$633	3.46	$813	1.58	$497
15	3.66	$646	3.22	$829	1.76	$438
16	3.11	$817	2.62	$1,012	2.06	$424

Source: University of California, Davis

Societally cost-effective efficiency measures with TDV$/$ greater than one or greater than either battery or PV systems can reduce TDV 5-40 percent across building types and climate zones with the PV and battery systems contributing the remaining TDV reductions to reach or approach ZNE-TDV.

Differences in upgrade cost-effectiveness across climate ones can be significant and are caused by interactions between the timing of energy savings for an upgrade along with climate zone TDV factor hourly shapes and climate zone weather patterns.

Batteries can achieve ZNE-TDV for all building types in all climate zones when there is not a limit on their maximum capacity, and they are allowed to both charge from the grid and discharge net power to the grid. Some efficiency upgrades are more cost-effective than batteries so that packages of these efficiency measures with batteries are more cost-effective than only batteries.

With 80 percent of roof area available, roof top PV systems can reach ZNE-TDV for single story buildings with lower energy use intensity (EUI) in all climate zones, but not for restaurants.

In all climate zones the societal return on investment, TDV$/$, for batteries is less than for PV systems. This means that the cost optimum packages of measures may include fewer efficiency upgrades when combined with PV than for batteries, particularly in climate zones where the difference between TDV$/$ for batteries and PV is large. Often, the measures included in the battery package are only a little bit less TDV$/$ cost effective than PV but may reduce the cost of reducing greenhouse gas emissions relative to PV. In the future, as more PV systems are connected to the grid, the TDV value of building attached PV systems is expected to decrease and this decrease may be faster than the decrease in cost of the PV systems. Many of the efficiency measures save energy at peak TDV times and may have an increase in TDV factor value. So future TDV factor values may bring more efficiency measures into the optimum packages.

In the high-rise or single story high EUI buildings cannot reach ZNE-TDV with roof top PV systems larger difference in TDV$/$ between PV systems where the threshold would now be TDV$/$>1 and battery systems can result in an efficiency measure being included with PV systems but not included with battery systems.

Utility Bill Analysis

The additional construction cost for upgrades was added to the change in the 30-year net present value of the utility bills at a 5 percent discount rate to calculate the builder or owner total cost net present value. For efficiency plus PV packages in all climate zones the utility bills are reduced enough to more than pay back the additional construction cost of upgrades so that there was a net savings to the builder or owner. For efficiency plus battery packages the utility bills were reduced for some building types in some climate zones but in other climate zones the utility bills increased. Battery utility bills can be sensitive to charging power that increases the demand kW from the baseline scenarios making the upgrade ineligible for the original tariff. For example, the battery utility bill savings net present value more than pays back the cost of the efficiency plus battery upgrades for the multitenant light commercial building type in some climate zones but not in others. However, the efficiency plus battery upgrades increases the utility bills for the other building types in several climate zones (Table 21). These complex trends are likely the result of different tariff structures and eligibility rules across different IOUs with changes from one tariff to another between baseline and upgrade cases having a significant impact.

Table 21: Battery System Utility Bill Impact

	Climate Zones where Efficiency plus Battery Systems:		
Building Type	**Reduce utility bills enough to reach net present value savings**	**Reduce utility bills but net present value cost increase**	**Increase utility bills**
Warehouse		6, 8, 10, 12, 14-15	1-5, 7, 9, 11, 13, 16
Large Office		7	1-6, 8-16
Retail Standalone		6, 7, 8, 9	10, 14-16
Multitenant Light Commercial	1-5, 7, 11-13, 16	6, 8, 9, 10, 14, 15	

Source: University of California, Davis

Very large battery systems are required to reach ZNE-TDV in large buildings. This study did not investigate the industrial tariffs and so very large battery systems were allowed to use commercial utility tariffs even if the increased demand kW power would make them ineligible so the utility bills for these battery systems are expected to be underestimates.

Battery systems can increase utility bills depending on how charging is managed and the impact on tariff eligibility rules, fixed charges (meter charges), and demand charges.

The TDV savings of batteries are sensitive to discharging timing and power.

Combining PV and battery systems can achieve ZNE-TDV for all building types in all climate zones and has the potential to achieve a zero impact on NPV utility bill using the assumptions discussed previously.

GHG Emissions Reductions Costs

The $/tonne CO_2e reduction for battery systems is lower than for PV. Batteries discharge at high TDV factor hours that align relatively well with high greenhouse gas intensity hours. In contrast PV systems export energy when the grid greenhouse gas intensity is already very low (Table 22).

The efficiency upgrades selected in the optimum packages typically have a lower cost per tonne CO_2e greenhouse gas emissions saved than either PV or batteries. Efficiency upgrades reduce the cost per tonne CO_2e greenhouse gas emissions saved compared to reaching ZNE-TDV with battery or PV alone.

Some individual efficiency upgrades in some climate zones had lower upgrade additional construction cost per tonne carbon emissions saved over 30 years compared to battery or PV alone.

Table 22: Efficiency Upgrade Additional Construction Cost per Tonne Carbon Emissions Saved Over 30 Years

	Climate Zone and City				
Efficiency Upgrade	**CZ 1 Arcata** Cool Humid	**CZ 3 Oakland** Mild Humid	**CZ 12 Sacramento** Hot Summer Mediterranean	**CZ 15 Palm Springs** Hot Desert	**CZ 16 Blue Canyon** Mountain
HDD (65F)	4829	2637	2495	783	5410
CDD (65F)	3	155	1213	4336	470
Heat Pump Water Heater*	A) $110 B) $52 C) $24	A) $108 B) $50 C) $22	A) $109 B) $51 C) $23	A) $107 B) $50 C) $21	A) $139 B) $76 C) $30
RTU Heat Pump Heating	B) $71	B) $120	B) $74	B) $658	B) $94
Water Loop Heat Pump	A) Negative C) $11	A) Negative C) $18	A) Negative C) $19	A) Negative C) $81	A) Negative C) $12
Additional Wall Insulation	A) $1,671 B) $230	A) $3,971 B) $49	A) $2,309 B) $332	A) $2,354 B) $349	A) $1,157 B) $185
High Efficacy LED	A) $22 B) $2559	A) Negative B) $565	A) $31 B) $413	A) Negative B) $233	A) Negative B) $577
Supply Duct Sealing*	A) $46	A) $49	A) $48	A) $53	A) $56

(A) Large Office (B) Retail Standalone (C) Highrise Multifamily, * Overestimate of cost per tonne CO_2e reductions because upgrade not credited with reduction in required HVAC system size.

Source: University of California, Davis

Upgrading to a heat pump storage tank water heater from an electric resistance baseline is one of the most cost-effective ways to reduce CO_2e emissions. The heat pump water heaters significantly increase efficiency and reduce electric energy consumption including during peak marginal greenhouse gas intensity times. The primary driver of the differences between building types is the quantity of hot water used per water heater with larger hot water uses resulting in greater energy savings and therefore greater CO_2e savings for the same upgrade cost. The large office has relatively low hot water usage per water heater, the retail stand alone has moderate hot water usage, and the high-rise multifamily has high hot water usage. Because heat pump water heaters remove heat from the interior conditioned spaces in a building, they can reduce cooling energy use in hot climates and increase heating usage in cool climates. This can be seen in the trend of cost per tonne CO_2e savings higher in cool climates and lower in hot climates.

Upgrading the rooftop packaged units (RTUs) from gas furnace heating to heat pump heating results in relatively cost-effective CO_2e reduction in CZ 1, 3, 12, and 16. CZ 1, 3, and 16 have a large number of heating degree days and very small number of cooling degree days, so that the heat pump operating time and, therefore, energy savings and emissions reduction is large. In CZ 12 the RTU capacity for heating is very close to cooling so that the cost is relatively low and there are still a significant number of heating degree days leading to significant emissions savings. CZ 15 has 783 Heating Degree Days (HDD (65)) and 4336 Cooling Degree Days (CDD (65)) and much more extreme hot temperatures than cold temperatures so upgrading the RTU to heat pump heating requires a much larger capacity RTU with increased cost and the heat pump does not operate in heating mode for enough hours to save much energy and CO_2e.

In large buildings that use hot water recirculation loops to provide heat, such as the large office VAV reheat system and the high-rise multifamily fan coil units, a large air to water heat pump can replace the typical conventional gas fueled boiler. The air to water heat pump has a slightly higher equipment cost than the conventional boiler or a condensing boiler. Depending on the detailed building design the cost savings from reducing or eliminating gas pipes can reduce the additional construction cost or even make the total construction cost less than baseline. This modest construction cost increase or below baseline construction cost paired with the large energy savings from the heat pump led to very low or negative cost per tonne CO_2e reduction. For example, in the high-rise multifamily building we assumed that gas piping would still be needed for gas ranges and ovens in the residential units so that the boiler gas piping costs reduce the construction cost premium for the water loop heat pump upgrade. In the large office there were no other gas end uses so that replacing the boiler led to an all-electric building that did not need any gas pipes reducing cost more than the equipment cost premium for the heat pump so that the construction cost was less than baseline and the cost per tonne CO_2e reduction was negative.

Upgrading wall insulation for the heavy mass walls in the Retail Standalone building type has variable cost per tonne CO_2e saved across climate zones likely because the baseline wall insulation requirement is different in the different climate zones. In climate zone 3 the baseline heavy mass wall insulation requirement is quite low and additional insulation has a large energy savings resulting in low cost per tonne CO_2e saved. For heavy mass walls climate zones 1, 12, 15, and 16 all have higher baseline insulation requirements and the diminishing returns to adding more insulation result in higher cost per tonne CO_2e saved. For the metal framed walls of the large office building type, all climate zones have fairly high baseline insulation requirements and the diminishing returns to adding more insulation result in very high cost per tonne CO_2e saved.

High efficacy LED lighting upgrades significantly reduce lighting energy consumption and also reduce waste heat generated in the building. In hot climates this reduction in waste heat reduces cooling energy consumption so that there is a double benefit reducing the cost per CO_2e reduction sometimes even resulting in a reduction in construction cost and listed in the table with a negative cost per tonne CO_2e saved. In cold climates reducing waste heat increases heating gas consumption reducing the CO_2e saved and resulting in higher cost per tonne CO_2e saved. In the large office building upgrades to a combination of high efficacy LED lighting in zones with the most daylight and very high efficacy LED lighting in zones without daylight in climate zones 3, 15, and 16 reduced the size of the HVAC cooling systems so much that upgrade construction costs were lower than baseline and there is a negative cost per tonne CO_2e saved.

TDV Favors NG

The median TDV factor for electricity is larger than natural gas at corresponding time steps. For example, in climate zone 12 the median electricity TDV factor is 2.51 times the median natural gas TDV factor in the same units (kBtu/kWh) at corresponding time steps. This means that on a TDV basis natural gas combustion space heating and water heating is favored over electric options when the construction costs are similar. This TDV preference for natural gas leads to natural gas hot water heaters being selected in multiple building types even though it increases greenhouse gas emissions. Heat pumps significantly increase heating efficiency above natural gas combustion and electric resistance but whether this increase is sufficient to overcome the TDV preference for natural gas depends significantly on heat pump costs, heat pump sizing, and selection of heat pump equipment efficiency curves that depend on outdoor conditions and supply temperatures. Potential future work could investigate heat pump space heating and domestic water heating in greater detail than was possible in this broad study.

Upgrading from the lowest cost electric resistance storage tank water heaters to natural gas fueled storage tank water heater will require additional natural gas piping and exhaust piping but would reduce the capacity of the electrical circuit required to that location. If the length of natural gas piping required is relatively short and exhaust piping relatively inexpensive then the natural gas fueled storage tank water heater will be the most TDV cost-effective option. If the length of natural gas piping required is longer and or the exhaust piping is more expensive than the heat pump water heater will be the most TDV cost-effective option. Detailed building designs are needed to estimate the length of natural gas piping and the cost of exhaust piping accurately enough to determine the most TDV cost-effective option. Since detailed plans were not available for the buildings considered in this study, we selected heat pump storage tank water heaters to be the upgrade option from the baseline of electric resistance storage tank water heaters in all building types except the warehouse where the simple layout allowed us to estimate that the natural gas line length was short.

Upgrading from conventional boilers to large air to water heat pumps for heating hot water loops in large buildings reduces TDV. This large heat pump upgrade increases the equipment installed cost but has the potential to decrease total construction costs if there are no other natural gas uses so that the expense of natural gas piping and exhaust piping is eliminated. The natural gas infrastructure cost savings depend on specific site locations and detailed building designs. For example, in the large office building type this study roughly estimated that completely eliminating natural gas for the building would save at least $241,000 and lead to a net decrease in construction cost for the heat pump upgrade scenario of $155,000. Very detailed building HVAC mechanical systems designs are required to estimate any change in costs for the hot water loop piping, pumps, and VAV reheat coil so these were not considered here and are an area for possible future work. With these assumptions, the large air to water heat pumps were cost-effective with TDV$/$>1 and TDV$/$>batteries in all California climate zones.

Window Upgrades

The Warehouse was modeled with the office windows facing north. The window upgrades decrease U-value and slightly increase the solar heat gain coefficient. In heating dominated climate zones both of these performance changes are valuable so that the window upgrades are part of the optimum package. In cooling dominated and mild climates the increase in solar heat gain coefficient reduces the benefits of the decrease in U-value and the window upgrades are not selected. The particular window upgrades selected in this study were recommended by Skanska as the most typical low-cost options (Skanska, 2019). Future work could investigate other window upgrade options that reduced both U-value and solar heat gain coefficient that may be more likely to be cost-effective in hot climates.

Results Details by Building Type

Building Type: Warehouse

Applicable Upgrade Measures

The following summarizes the non-HVAC energy conservation upgrade measures applicable to the warehouse:

- Photovoltaic Panels – Placed on Fine Storage rooftop optimum tilt
- Battery Storage
- Thermal Mass - increase slab floor thickness
- Fenestration
    - High Performance Windows
    - Skylights replacing baseline Light Tubes
- Ceiling Fans
- Blinds and Shades
- Cool Roof - only on fine storage because bulk storage is not a cooled space
- Domestic Hot Water Heating Equipment
    - Natural gas fueled Storage Tank water heaters
    - Natural gas fueled Condensing Storage Tank water heaters
    - Electric Heat Pump Storage Tank water heaters
    - Natural gas fueled Tankless water heaters
- Increased Wall and Roof Insulation
- Daylighting and Occupancy Lighting/Receptacle Controls
- High Efficiency Lighting Technology - Fixture types are Troffer in Office and High Bay in Storage spaces
- Phase Change Materials – Office space top surface of drop ceiling
- Aerosol Envelope Sealing – Most likely to pay off for office space that is the only space with typical heating and cooling setpoints

An additional measure that was unique to the warehouse was the increase of the demising wall insulation, with the goal of minimizing heat transfer between the cooled and uncooled storage spaces.

The applicable HVAC upgrade measures modeled are:

- Increased office RTU Efficiency
- Office RTU evaporative condenser air pre-cooling. (ICI CoilCool)

- Fine Storage evaporative condenser air pre-cooling. (ICI CoilCool)
- Office RTU evaporative condenser air pre-cooling and ventilation air pre-cooling. (ICI DualCool)
- Fine Storage RTU evaporative condenser air pre-cooling and outdoor air pre-cooling. (ICI DualCool)
- Fine Storage Indirect Evaporative Cooling for ventilation air (Seeley Climate Wizard)
- Fine Storage Indirect Evaporative Cooling for both ventilation air and return air (Seeley Climate Wizard)

Individually Cost-Effective Measures

The following energy conservation measures were found to be TDV cost-effective, specifically to have a TDV dollar savings divided by dollar additional construction cost to calculate TDV return on investment TDV$/$ greater than one in one or more climate zones. Measures are listed in rough order of largest TDV$/$ return on investment across climate zones.

- Heat Pump Storage Tank Water Heater
- Natural gas fueled Storage Tank Water Heater
- Very High Efficacy Led Lighting – Fine Storage High Bay
- High Efficacy LED Lighting – Office Troffer
- Office Window - Add room side low-e coating on surface #4
- Office Window – Add thermal break to metal frame
- Very High Efficacy LED Lighting – Office Troffer
- Fine Storage Indirect Evaporative Cooling for ventilation air
- Office Wall Additional Insulation
- Natural gas fueled Tankless Water Heater
- Office Window – Add both room side low-e coating on surface #4 and thermal break to metal frame
- Daylighting and Occupancy Lighting Controls
- High office RTU DX Efficiency and Variable Speed Supply Fan
- Very high office RTU DX Efficiency and Variable Speed Supply Fan and Variable Speed Compressor

The following upgrades are individually cost-effective with TDV$/$ larger than one in one or more climate zones but less than both PV and Battery systems in all climate zones so that they were not simulated in the full matrix of interacting measures.

- Fine Storage Additional Wall Insulation
- Natural gas fueled Condensing Storage Tank Water Heater
- Fine Storage Additional Roof Insulation
- Office Wall More Additional Insulation
- Fine Storage RTU evaporative pre-cooling of condenser and outdoor air
- Demising Wall Insulation

The measures that achieve a TDV$/$ larger than either PV or Battery systems in one or more climate zones were then simulated in all possible combinations with interactions between all measures' energy savings and construction cost to find the most TDV cost-effective package of measures in each climate zone. For packages TDV cost-effective is defined as the societal cost calculated by adding the change in construction cost and the change in TDV dollars where the selected package achieves the largest total savings.

Cost-Effective Combinations of Measures

ZNE-TDV through Rooftop PV

When ZNE-TDV, as previously defined, is reached through the installation of rooftop PV, the combination of upgrades that were found to generate the largest societal cost savings defined as the change in construction cost minus the TDV dollar savings were included in the best performing packages. These packages include upgrades that reduce construction costs and or have a larger TDV dollar saved per dollar additional construction cost than PV.

- High Efficacy Led Lighting - Bulk Storage High Bay LED replacing metal halide (reduces construction cost)
- Very High Efficacy Led Lighting – Fine Storage High Bay replacing High Efficacy LED lighting required to meet code maximum lighting power density limit
- Installing natural gas fueled storage tank water heaters in place of electric resistance storage tank water heaters

Adding a thermal break to the metal window frames in the office area was selected in climate zones 1, 2, 3, 12, 16.

Adding indirect evaporative cooling for ventilation air in the fine storage area was selected in climate zones 15.

ZNE-TDV through Battery Storage

When ZNE-TDV, as previously defined, is reached through the installation of a battery energy storage system, the ECM's that were found to generate the largest societal cost savings defined as the additional construction cost minus the TDV dollar savings were selected in all climate zones are:

- Very High Efficacy Led Lighting – Office Troffers and Storage High Bay.
- Installing a heat pump storage tank water heater in place of electric resistance storage tank water heater was selected in climate zones 1-8 and 10-15.
- Installing a natural gas fueled storage tank water heater in place of electric resistance storage tank water heater was selected in climate zones 9 and 16.
- Adding a thermal break to the metal window frames in the office area was selected in climate zones 1, 3, 12, 16.
- Adding a room side low emissivity coating to the windows in the office area was selected in climate zone 2.
- Upgrading the Office RTU efficiency to a COP of 3.85 with a variable speed supply fan was selected in the climate zones 4, 6, 8-15.
- Adding indirect evaporative cooling for ventilation air in the fine storage area was selected in climate zones 11, 14-15.

Table 23 shows a summary of the results for efficiency and battery upgrades, while Table 24 shows a summary of the results for efficiency upgrades with solar

Table 23: Summary of Results – Efficiency + Battery

CZ	Most cost-effective package if using Efficiency + Battery Energy Storage to reach ZNE-TDV	Battery Capacity (kW and kWh)	Total Upgrade Cost ($1000s)	TDV$/$ for Battery ZNE Package	Societal Cost (upgrade + change in TDV $1000s)	Builder Owner Cost (upgrade + change in Utility NPV $1000s)	Upgrade cost $ per tonne 30 yr. CO_2e reduction
1	Office Windows Frame Thermal Break, Very High Efficacy LED Lights All Areas, Heat Pump Water Heater	307	$209	1.9	($195)	$289	$467
2	Office Windows Roomside Coating, Very High Efficacy LED Lights All Areas, Heat Pump Water Heater	307	$209	1.8	($164)	$254	$467
3	Office Windows Frame Thermal Break, Very High Efficacy LED Lights All Areas, Heat Pump Water Heater	333	$215	1.7	($158)	$279	$441
4	Increased Office RTU Efficiency, Very High Efficacy LED Lights All Areas, Heat Pump Water Heater	313	$201	1.9	($181)	$296	$440
5	Very High Efficacy LED Lights All Areas, Heat Pump Water Heater	272	$189	1.9	($178)	$255	$473
6	Increased Office RTU Efficiency, Very High Efficacy LED Lights All Areas, Heat Pump Water Heater	310	$219	1.7	($151)	$173	$491

7	Very High Efficacy LED Lights All Areas, Heat Pump Water Heater	259	$167	2.2	($195)	$604	$442
8	Increased Office RTU Efficiency, Very High Efficacy LED Lights All Areas, Heat Pump Water Heater	316	$221	1.8	($179)	$178	$485
9	Increased Office RTU Efficiency, Very High Efficacy LED Lights All Areas, Natural Gas Water Heater	261	$168	2.4	($233)	$181	$454
10	Increased Office RTU Efficiency, Very High Efficacy LED Lights All Areas, Heat Pump Water Heater	412	$290	1.4	($113)	$343	$489
11	Increased Office RTU Efficiency, Indirect Evaporative Pre-cooling of Ventilation Air, Very High Efficacy LED Lights All Areas, Heat Pump Water Heater	373	$263	1.6	($148)	$343	$488
12	Increased Office RTU Efficiency, Office Window Frames Thermal Break, Very High Efficacy LED Lights All Areas, Heat Pump Water Heater	346	$244	1.6	($140)	$304	$487
13	Increased Office RTU Efficiency, Very High Efficacy LED Lights All Areas, Heat Pump Water Heater	294	$188	2.2	($222)	$332	$435
14	Increased Office RTU Efficiency, Indirect Evaporative Pre-cooling of Ventilation Air, Very High Efficacy LED	353	$260	1.7	($170)	$578	$516

	Lights All Areas, Heat Pump Water Heater						
15	Increased Office RTU Efficiency, Indirect Evaporative Pre-cooling of Ventilation Air, Very High Efficacy LED Lights All Areas, Heat Pump Water Heater	369	$244	1.9	($217)	$160	$444
16	Office Window Frames Thermal Break, Very High Efficacy LED Lights All Areas, Natural Gas Water Heater	307	$209	1.8	($164)	$402	$467

Source: University of California, Davis

Table 24: Summary of Results – Efficiency + PV

CZ	Most cost-effective package if using roof mounted PV with optimum tilt to reach ZNE-TDV	PV Capacity (kW DC at STC)	Total Upgrade Cost ($1000s)	TDV$/$ for PV ZNE Package	Societal Cost (upgrade + change in TDV $1000s)	Builder Owner Cost (upgrade + change in Utility NPV $1000s)	Upgrade cost $ per tonne 30 yr. CO_2e reduction
1	Office Window Frames Thermal Break, Very High Efficacy LED Lights in Storage Areas, Natural Gas Water Heater	87	$173	2.3	($231)	($193)	$1,502
2	Office Window Frames Thermal Break, Very High Efficacy LED Lights in Storage Areas, Natural Gas Water Heater	61	$122	3.1	($252)	($240)	$1,283

3	Office Window Frames Thermal Break, Very High Efficacy LED Lights in Storage Areas, Natural Gas Water Heater	63	$126	3.0	($247)	($221)	$1,249
4	Very High Efficacy LED Lights in Storage Areas, Natural Gas Water Heater	57	$113	3.4	($268)	($242)	$1,217
5	Very High Efficacy LED Lights in Storage Areas, Natural Gas Water Heater	58	$116	3.2	($251)	($246)	$1,080
6	Very High Efficacy LED Lights in Storage Areas, Natural Gas Water Heater	54	$109	3.4	($261)	($91)	$1,008
7	Very High Efficacy LED Lights in Storage Areas, Natural Gas Water Heater	60	$119	3.0	($243)	($117)	$1,031
8	Very High Efficacy LED Lights in Storage Areas, Natural Gas Water Heater	53	$107	3.7	($294)	($100)	$1,024
9	Very High Efficacy LED Lights in Storage Areas, Natural Gas Water Heater	54	$107	3.7	($294)	($105)	$997
10	Very High Efficacy LED Lights in Storage Areas, Natural Gas Water Heater	56	$111	3.6	($292)	($114)	$971
11	Very High Efficacy LED Lights in Storage Areas, Natural Gas Water Heater	66	$133	3.1	($279)	($253)	$1,268

12	Office Window Frames Thermal Break, Very High Efficacy LED Lights in Storage Areas, Natural Gas Water Heater	61	$123	3.1	($260)	($264)	$1,273
13	Very High Efficacy LED Lights in Storage Areas, Natural Gas Water Heater	64	$128	3.2	($282)	($265)	$1,218
14	Very High Efficacy LED Lights in Storage Areas, Natural Gas Water Heater	55	$109	3.9	($321)	($123)	$913
15	Indirect Evaporative Pre-cooling of Ventilation Air, Very High Efficacy LED Lights in Storage Areas, Natural Gas Water Heater	58	$124	3.7	($337)	($37)	$918
16	Office Window Frames Thermal Break, Very High Efficacy LED Lights in Storage Areas, Natural Gas Water Heater	73	$145	-3.1	($310)	($145)	$1,119

Source: University of California, Davis

Results Discussion: Warehouse

Water Heaters

In the warehouse building type, natural gas storage tank water heaters were selected in place of baseline electric resistance storage tank water heaters in some packages when they had a TDV$/$ greater than the heat pump hot water heaters. Building design details were not sufficient to determine the expected cost difference between a 240V electrical circuit and natural gas distribution plumbing so these cost changes were not considered. The switch to natural gas storage tank water heater may have higher cost in reality if the natural gas distribution plumbing is more expensive decreasing the TDV$/$. The natural gas storage tank water heater increased greenhouse gas emissions compared to the baseline electric resistance water heater.

Indirect Evaporative Cooling

IEC was considered for cooling return air from the warehouse fine storage space but was not predicted to be cost-effective on a TDV dollar savings per dollar increased construction cost basis. These results are likely because IEC systems were not credited with reduced RTU cooling equipment size reduction savings. Also, IEC technology is not as efficient for cooling from indoor return air temperatures down to a bit below wet-bulb temperature compared to being very efficient for cooling from high outdoor air temperatures to a bit below wet-bulb temperature.

Relatively little cooling is required in the fine storage area because of the high cooling temperature setpoint further contributing to lower cost-effectiveness for evaporative cooling technologies and indirect evaporative cooling of ventilation air only being cost-effective in very dry climate zones.

Windows

The Warehouse was modeled with the office windows facing north. The window upgrades decrease U-value and slightly increase the solar heat gain coefficient. The particular window upgrades selected in this study were recommended by Skanska as the most typical low-cost options (Skanska, 2019). In heating dominated climate zones both of these performance changes are valuable so that the window upgrades are part of the optimum package. In cooling dominated and some mild climates the increase in solar heat gain coefficient reduces the benefits of the decrease in U-value and the window upgrades are not selected.

Priorities for Future Work: Warehouse

Future work could consider the following options for the warehouse building type that were not considered in this study:

- Very large heat pump RTUs for the storage areas
- Multiple smaller RTUs instead of large RTUs
- Small indirect evaporative cooler for the office space
- Alternatives to unit heaters in the bulk storage area

Building Type: Large Office

Applicable Upgrade Measures

The following list summarizes the non-HVAC energy conservation upgrade measures applicable to the Large Office:

- Photovoltaic Panels – Rooftop flat
- Battery Storage
- High Efficiency Lighting Technology - Fixture types are Troffers
- Thermal Mass - increase slab floor thickness
- Fenestration
  - High Performance Windows
  - Window exterior overhangs – West and South+West orientations
  - Blinds and Shades
- Additional Daylighting and Occupancy Lighting Controls
- Ceiling Fans
- Cool Roof
- Domestic Hot Water Heating Equipment
  - Natural gas fueled Storage Tank water heaters
  - Natural gas fueled Condensing Storage Tank water heaters
  - Electric Heat Pump Storage Tank water heaters
  - Natural gas fueled Tankless water heaters
- Increased Wall and Roof Insulation
- Phase Change Materials – top surface of drop ceiling
- Aerosol Envelope Sealing – above ground exterior walls
- Traction elevator regenerative drive for increased efficiency

Upgrades to data center and IT closets were considered but were rejected due to insufficient information about usage schedules, baseline technologies, and the rapid pace of change as computation shifts from local servers to cloud based services.
In terms of HVAC, the list of tested upgrades was as follows:

- Supply duct sealing
- Indirect evaporative pre-cooling of ventilation air before air handler (Seeley Climate Wizard)
- Chiller evaporative condenser air pre-cooling. (ICI CoilCool)
- Condensing boiler for increased efficiency heating VAV reheat water loop
- Large air to water Heat Pump to heat VAV reheat water loop

What follows summarizes the results of the two-step process designed to determine the most cost-effective technology packages.

Individually Cost-Effective Measures

The following energy conservation measures were found to be TDV cost-effective, i.e. to have a TDV dollar savings divided by dollar additional construction cost to calculate TDV return on investment TDV$/$ greater than one in one or more climate zones. Measures are listed in rough order of largest TDV$/$ return on investment across climate zones.

The upgrades that both reduced TDV and resulted in a reduction in construction costs were:

- High Efficiency Lighting – LED troffers with high efficacy of 135 lumens per watt depending on climate zone and specific space in the building
- Large air to water Heat Pump to heat VAV reheat water loop – replaces only natural gas load in the building and, therefore, eliminates natural gas piping costs estimated at $155,000

The upgrades that are individually cost-effective with TDV$/$ larger than PV or Battery systems in one or more climate zones are:

- High Efficiency Lighting Technology - fixture types are Troffers upgrade to high efficacy LED or very high efficacy LED depending on climate zone and specific space in the building
- Supply duct sealing
- Indirect evaporative pre-cooling of ventilation air before air handler (Seeley Climate Wizard)
- Heat Pump Water Heaters – placed in core zones close to end use to avoid need for recirculation
- Chiller evaporative condenser air pre-cooling (ICI CoilCool)
- Condensing boiler
- Large air to water Heat Pump to heat VAV reheat water loop
- Traction elevator regenerative drive for increased efficiency

Upgrades listed below are individually cost-effective with TDV$/$ larger than one in one or more climate zones but less than both PV and Battery systems in all climate zones so that they were simulated in the full matrix of interacting measures paired with PV but not with batteries.

- Increased Roof Insulation (only CZ 15 TDV$/$>1)
- Additional Daylighting and Occupancy Lighting Controls (only CZ 15 TDV$/$>1)

The measures that achieve a construction cost savings or a TDV$/$ larger than either PV or Battery systems in one or more climate zones were then simulated in all possible combinations with interactions between all measures' energy savings and construction cost to find the most TDV cost-effective package of measures in each climate zone. For packages TDV cost-effective is defined as the societal cost calculated by adding the change in construction cost and the change in TDV dollars where the selected package achieves the largest total savings.

Cost-Effective Combinations of Measures

ZNE-TDV through Rooftop PV and Battery Systems

When ZNE-TDV, as previously defined, is approached through the installation of rooftop PV systems, the total amount of PV is constrained by the assumed 80 percent of available roof area so that measures that pay off with a TDV$/$ greater than one or have a construction cost savings will achieve a less than zero societal cost (Construction Cost - TDV$ savings) will be included in the optimum packages. When ZNE-TDV, as previously defined, is reached through the installation of a battery energy storage system, measures compete with additional battery capacity so that only measures that pay off better than batteries on a TDV$/$ and societal cost (Construction Cost - TDV$ savings) basis will be included in the optimum package.

The upgrades that were most cost-effective and were selected in the optimum packages in all climate zones are:

- Supply duct sealing
- High Efficiency Lighting – LED troffers with high or very high efficiency depending on climate zone and specific space in the building
- Heat Pump Water Heaters – placed in core zones close to end use to avoid need for recirculation
- Large air to water Heat Pump to heat VAV reheat water loop

Other efficiency measures were cost-effective in a subset of climate zones for both PV and Battery combinations or for one or the other:

Indirect evaporative pre-cooling of ventilation air before air handler (Seeley Climate Wizard)

Addition of indirect evaporative pre-cooling (IEC) of ventilation air (Seeley Climate Wizard) was cost-effective with efficiency plus PV packages (TDV$/$>1) in all climate zones except for the high humidity climate zones 1, 3, and 5. For efficiency plus battery packages the IEC was cost-effective (TDV$/$>Batteries) in low humidity climate zones 4 and 8-15 as well as climate zone 6 but not in more humid coastal climate zones 1-3, 5, 7, and relatively low cooling 16. Future addition of cost credit for IEC enabling chiller downsizing would likely make this measure cost-effective in more climate zones.

Chiller condenser air evaporative pre-cooling (ICI CoilCool)

Addition of chiller condenser air evaporative pre-cooling (ICI CoilCool) was cost-effective with efficiency plus PV packages (TDV$/$>1) in low humidity climate zones 11-15 and also in climate zone 2. Addition of chiller condenser air evaporative pre-cooling (ICI CoilCool) was cost-effective with efficiency plus battery packages (TDV$/$>Batteries) in low humidity climate zones 11-13 and 15 and also in climate zone 2. Future addition of cost credit for condenser air evaporative pre-cooling enabling chiller downsizing would likely make this measure cost-effective in more climate zones.

Traction elevator regenerative drive for increased efficiency

Adding a regenerative drive to the baseline traction elevator was cost-effective in all climate zones for efficiency plus PV packages (TDV$/$>1) but only in climate zone 10 for efficiency plus battery packages (TDV$/$>Batteries). Table 25 shows a summary of the results for efficiency upgrades with battery and Table 26 summaries efficiency upgrades with PV.

Table 25: Summary of Results – Efficiency + Battery

CZ	Most cost-effective package if using Battery Energy Storage to reach ZNE-TDV	Battery Capacity (kW and kWh)	Total Upgrade Cost ($1000s)	TDV$/$ for Battery ZNE Package	Societal Cost (upgrade + change in TDV $1000s)	Builder Owner Cost (upgrade + change in Utility NPV $1000s)	Upgrade cost $ per tonne 30 yr. CO_2e reduction
1	Hot Water Loop Heat Pump, Supply Duct Sealing, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	17785	$11,795	2.1	$(13,370)	$12,459	$411
2	Hot Water Loop Heat Pump, Supply Duct Sealing, Heat Pump Water Heaters, Evaporative Precooling of Chiller Condenser Air, High and Very High Efficacy LED Lighting	20561	$13,710	1.9	$(13,008)	$15,524	$425
3	Hot Water Loop Heat Pump, Supply Duct Sealing, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	21766	$13,652	1.9	$(12,291)	$17,005	$402
4	Hot Water Loop Heat Pump, Supply Duct Sealing, Heat Pump Water Heaters, Indirect Evaporative Precooling of Ventilation Air, High and Very High Efficacy LED Lighting	20318	$13,111	2.1	$(14,065)	$13,536	$408
5	Hot Water Loop Heat Pump, Supply Duct Sealing, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	18001	$12,188	2.1	$(13,677)	$12,552	$428

6	Hot Water Loop Heat Pump, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	21051	$14,842	1.8	$(12,376)	$15,935	$457
7	Hot Water Loop Heat Pump, Supply Duct Sealing, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	17899	$11,174	2.4	$(15,396)	$(11,712)	$400
8	Hot Water Loop Heat Pump, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	20352	$14,214	2.0	$(14,216)	$14,991	$445
9	Hot Water Loop Heat Pump, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	16517	$10,700	2.6	$(17,641)	$9,272	$394
10	Evaporative Precooling of Chiller Condenser Air, Hot Water Loop Heat Pump, Supply Duct Sealing, Heat Pump Water Heaters, Indirect Evaporative Precooling of Ventilation Air, Elevator Regenerative Drive, High and Very High Efficacy LED Lighting	25761	$18,275	1.5	$(9,886)	$21,982	$459
11	Evaporative Precooling of Chiller Condenser Air, Hot Water Loop Heat Pump, Supply Duct Sealing, Heat Pump Water Heaters, Indirect Evaporative	22577	$15,987	1.8	$(12,307)	$16,976	$442

	Precooling of Ventilation Air, High and Very High Efficacy LED Lighting						
12	Evaporative Precooling of Chiller Condenser Air, Hot Water Loop Heat Pump, Supply Duct Sealing, Heat Pump Water Heaters, Indirect Evaporative Precooling of Ventilation Air, High and Very High Efficacy LED Lighting	22321	$15,787	1.7	$(11,668)	$17,238	$449
13	Evaporative Precooling of Chiller Condenser Air, Hot Water Loop Heat Pump, Supply Duct Sealing, Heat Pump Water Heaters, Indirect Evaporative Precooling of Ventilation Air, High and Very High Efficacy LED Lighting	18067	$11,568	2.5	$(17,024)	$8,907	$387
14	Hot Water Loop Heat Pump, Supply Duct Sealing, Heat Pump Water Heaters, Indirect Evaporative Precooling of Ventilation Air, High and Very High Efficacy LED Lighting	21866	$15,537	1.9	$(13,227)	$15,531	$454
15	Evaporative Precooling of Chiller Condenser Air, Hot Water Loop Heat Pump, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	23007	$14,653	2.1	$(16,613)	$13,875	$395
16	Hot Water Loop Heat Pump, Supply Duct Sealing, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	18591	$11,212	2.3	$(14,539)	$12,513	$375

Source: University of California, Davis

Table 26 Summary of Results – Efficiency + PV

CZ	Most cost-effective package if using roof mounted PV with optimum tilt to reach ZNE-TDV	PV Capacity (kW DC at STC)	Total Upgrade Cost ($1000s)	TDV Reduction	TDV$/$ for PV ZNE Package	Societal Cost (upgrade + change in TDV $1000s)	Builder Owner Cost (upgrade + change in Utility NPV $1000s)	Upgrade cost $ per tonne 30 yr. CO_2e reduction
1	Hot Water Loop Heat Pump, Supply Duct Sealing, Elevator Regenerative Drive, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	52	1232	12%	2.3	$(1,557)	$(5,471)	$373
2	Hot Water Loop Heat Pump, Evaporative Precooling of Chiller Condenser Air, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Elevator Regenerative Drive, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	52	1728	15%	2.1	$(1,885)	$(7,684)	$523
3	Hot Water Loop Heat Pump, Supply Duct Sealing, Elevator Regenerative Drive, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	52	1186	13%	2.4	$(1,641)	$(6,711)	$416
4	Hot Water Loop Heat Pump, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Elevator Regenerative Drive, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	52	1683	16%	2.3	$(2,203)	$(7,946)	$517
5	Hot Water Loop Heat Pump, Supply Duct Sealing, Elevator Regenerative	52	1230	13%	2.3	$(1,547)	$(7,011)	$441

	Drive, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting							
6	Hot Water Loop Heat Pump, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Elevator Regenerative Drive, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	52	1630	15%	2.2	$(2,025)	$(4,763)	$517
7	Hot Water Loop Heat Pump, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Elevator Regenerative Drive, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	52	1627	15%	2.2	$(1,949)	$(10,435)	$510
8	Hot Water Loop Heat Pump, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Elevator Regenerative Drive, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	52	1617	17%	2.7	$(2,763)	$(5,402)	$454
9	Hot Water Loop Heat Pump, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Elevator Regenerative Drive, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	52	1613	18%	2.8	$(2,851)	$(5,586)	$457
10	Hot Water Loop Heat Pump, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Elevator Regenerative Drive, Heat Pump Water	52	1662	18%	2.7	$(2,756)	$(5,636)	$459

	Heaters, High and Very High Efficacy LED Lighting							
11	Hot Water Loop Heat Pump, Evaporative Precooling of Chiller Condenser Air, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Elevator Regenerative Drive, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	52	1670	19%	2.9	$(3,106)	$(8,877)	$397
12	Hot Water Loop Heat Pump, Evaporative Precooling of Chiller Condenser Air, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Elevator Regenerative Drive, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	52	1724	17%	2.4	$(2,388)	$(8,435)	$471
13	Hot Water Loop Heat Pump, Evaporative Precooling of Chiller Condenser Air, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Elevator Regenerative Drive, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	52	1667	19%	2.9	$(3,185)	$(9,220)	$399
14	Hot Water Loop Heat Pump, Evaporative Precooling of Chiller Condenser Air, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Elevator Regenerative	52	1638	19%	3.1	$(3,357)	$(5,797)	$429

	Drive, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting							
15	Hot Water Loop Heat Pump, Evaporative Precooling of Chiller Condenser Air, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Elevator Regenerative Drive, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	52	1673	22%	3.8	$(4,731)	$(6,833)	$354
16	Hot Water Loop Heat Pump, Supply Duct Sealing, Indirect Evaporative Precooling of Ventilation Air, Elevator Regenerative Drive, Heat Pump Water Heaters, High and Very High Efficacy LED Lighting	52	1546	13%	1.9	$(1,407)	$(6,515)	$420

Source: University of California, Davis

Results Discussion: Large Office

Efficiency plus PV packages reduce the total TDV from baseline by 12 percent to 22 percent. One reason that this reduction is relatively small is due to the very large energy consumption from the data center and IT closets. Removing data center energy consumption roughly doubles the percentage of TDV reduction from efficiency plus PV packages. Efficiency plus PV packages reduce utility bills enough to more than pay back the increased construction costs so that builder owner 30-year net present value costs decrease significantly from baseline.

Efficiency plus battery packages achieve ZNE-TDV and societal cost savings. In climate zones 7, 9, 13-15 efficiency plus batteries reduce utility bills. In only climate zone 7 utility plus batteries reduce utility bills enough for the 30-year net present value of the utility bill savings to more than pay for the construction cost increase of the building upgrade. In climate zones 1-6, 8, 10-12, and 16, efficiency plus batteries increase utility bills so that builder owner costs increase both for construction cost and for operating costs so that builder owner net present value costs increase significantly compared to baseline. These utility bill results use tariff structures of the highest power demand kW offered by the utilities even though the battery three-hour charging strategy results in power levels higher than these tariffs allow. Changes in tariff structure and in charging strategy may change these results but only big changes would shift this overall trend.

Priorities for Future Work: Large Office

For battery packages, investigate tariff structures, tariff eligibility, and construction cost for electrical service at power levels higher than the commercial tariffs allow.

VAV reheat hot water systems have very low efficiency during very low reheat demand times. Improving EnergyPlus modelling of these systems at very low load with large losses in any boiler(s), hot water distribution pipes, and issues like valve leak-by are expected to make upgrades like condensing boilers or heat pumps even more cost-effective. In addition, a small heat recovery chiller or heat pump could further enhance efficiency by cooling the chilled water loop and moving thermal energy to the hot water loop to satisfy the low reheat load times while avoiding activating large boilers or large heat pumps.

Large commercial buildings typically bring in a larger outside air flow rate than required for minimum ventilation to maintain a positive pressure inside the building. The amount of air flow required depends significantly on building envelope and exhaust shaft leakage. Because these leakage rates can vary significantly from building to building most simulations, including those developed in this study, assume outside air flow rates required for minimum ventilation. This significantly underestimates the benefits of envelope sealing and somewhat underestimates the benefits of air cooling and heating efficiency upgrades. Future work could improve models used in this study as well as those used for code compliance by measuring a larger sample of large commercial buildings to predict the range of expected outside air flow, envelope leakage, and exhaust shaft leakage.

Building Type: Retail Standalone

Applicable Upgrade Measures

The following list summarizes the non-HVAC energy conservation upgrade measures applicable to the warehouse:

- Photovoltaic Panels – Rooftop optimum tilt
- Battery Storage
- Domestic Hot Water Heating Equipment
- Electric heat pump storage tank water heaters
- Natural gas fueled storage tank water heaters
- Natural gas fueled condensing storage tank water heaters
- Natural gas fueled tankless water heaters
- High Efficiency Lighting Technology – Upgrade troffers from linear fluorescent to LED and LED baseline for task and accent lighting, second level upgrade to very high effectiveness LED troffers
- Daylighting and Occupancy Lighting Controls
- Increased Wall and Roof Insulation
- Aerosol Envelope Sealing (Aerobarrier)
- Exterior window overhangs
- Cool Roof - only on fine storage because bulk storage is not a cooled space
- Fenestration
- High Performance Windows – additional room side Low-E coating and or frame thermal break
- Skylights replacing baseline Light Tubes
- Blinds and Shades
- Thermal Mass - increase concrete slab floor thickness

The applicable HVAC upgrade measures modeled are:

- RTU evaporative condenser air pre-cooling and ventilation air pre-cooling (ICI DualCool)
- RTU evaporative condenser air pre-cooling (ICI CoilCool)
- Increased office RTU COP, variable speed supply fan, variable speed condenser
- RTU heat pumps for heating

What follows summarizes the results of the two-step process designed to determine the most cost-effective technology packages.

Individually Cost-Effective Measures

The following energy conservation measures were found to be TDV cost-effective, specifically to have a TDV dollar savings divided by dollar additional construction cost to calculate TDV return on investment TDV$/$ greater than one in one or more climate zones. Measures are listed in rough order of largest TDV$/$ return on investment across climate zones.

- Increased Wall Insulation
- Domestic Hot Water Heating Equipment
    - Electric heat pump storage tank water heaters
    - Natural gas fueled storage tank water heaters
    - Natural gas fueled condensing storage tank water heaters
    - Natural gas fueled tankless water heaters

- High Efficiency Lighting Technology – Upgrade troffers from linear fluorescent to LED and LED baseline for task and accent lighting, second level upgrade to very high effectiveness LED troffers
- RTU evaporative condenser air pre-cooling and ventilation air pre-cooling (ICI DualCool)
- RTU evaporative condenser air pre-cooling (ICI CoilCool)
- RTU heat pumps for heating
- Increased office RTU COP, variable speed supply fan.

Upgrades listed below are individually cost-effective with TDV$/$ larger than one in one or more climate zones but less than PV and Battery systems in all climate zones so that they were not simulated in the full matrix of interacting measures.

- Daylighting and Occupancy Lighting Controls
- Increased Wall and Roof Insulation
- Aerosol Envelope Sealing (Aerobarrier)
- Daylighting and Occupancy Lighting Controls.

The measures that achieve a TDV$/$ larger than either PV or Battery systems in one or more climate zones were then simulated in all possible combinations with interactions between all measures' energy savings and construction cost to find the most TDV cost-effective package of measures in each climate zone. For packages TDV cost-effective is defined as the societal cost calculated by adding the change in construction cost and the change in TDV dollars where the selected package achieves the largest total savings.

Cost-Effective Combinations of Measures

The upgrades that were found to have largest societal cost savings defined as the change in construction cost minus the TDV dollar savings were included in the best performing packages. The packages include upgrades that reduce construction costs and or have a larger TDV dollar saved per dollar additional construction cost than PV and batteries in all climate zones are:

- Electric heat pump storage tank water heaters.
- High or Very High Efficacy LED Lighting - Troffers

The following upgrades were more cost-effective than PV in the specific climate zones listed.

- Additional wall insulation level 1 in CZ 2-10 and 15
- RTU evaporative condenser air pre-cooling and outdoor air pre-cooling (ICI DualCool) in CZ 11, 13, and 15

The following upgrades were more cost-effective than batteries in the specific climate zones listed.

- RTU evaporative condenser air pre-cooling and outdoor air pre-cooling (ICI DualCool) in CZ 2-4 and 6-15
- Wall insulation addition level 1 in CZ 3-9 and 12-14, 16 and level 2 in CZ 2, 10-11, 15
- Lighting very high efficacy LED troffers instead of high efficacy LED in CZ 7-8, 10-15

Table 27 provides a summary of results for efficiency and battery upgrades, and Table 28 shows a summary of the results for efficiency and solar upgrades.

Table 27: Summary of Results – Efficiency + Battery

CZ	Most cost-effective package if using Efficiency + Battery Energy Storage to reach ZNE-TDV	Battery Capacity (kW and kWh)	Total Upgrade Cost ($1000s)	TDV$/$ for Battery ZNE Package	Societal Cost (upgrade + change in TDV $1000s)	Builder Owner Cost (upgrade + change in Utility NPV $1000s)	Upgrade cost $ per tonne 30 yr. CO_2e reduction
1	Heat Pump Water Heaters, High Efficacy LED Lighting	618	$432	2.0	($445)	$595	$474
2	Heat Pump Water Heaters, Exterior Wall Insulation 2, High Efficacy LED Lighting	662	$488	2.0	($505)	$581	$415
3	Heat Pump Water Heaters, Exterior Wall Insulation, High Efficacy LED Lighting	667	$440	2.0	($422)	$531	$408
4	Heat Pump Water Heaters, Exterior Wall Insulation, High Efficacy LED Lighting	684	$446	2.2	($514)	$525	$404
5	Heat Pump Water Heaters, Exterior Wall Insulation, High Efficacy LED Lighting	534	$384	2.2	($444)	$460	$434
6	Heat Pump Water Heaters, Exterior Wall Insulation, High Efficacy LED Lighting	646	$466	1.9	($416)	$372	$457
7	Heat Pump Water Heaters, Exterior Wall Insulation, Very High Efficacy LED Lighting	491	$337	2.4	($487)	$271	$407

8	Heat Pump Water Heaters, Exterior Wall Insulation, Very High Efficacy LED Lighting	657	$472	2.1	($512)	$348	$443
9	Heat Pump Water Heaters, Exterior Wall Insulation, High Efficacy LED Lighting	563	$368	2.7	($639)	$261	$389
10	Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heaters, Exterior Wall Insulation 2, Very High Efficacy LED Lighting	759	$620	1.6	($396)	$2,843	$474
11	Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heaters, Exterior Wall Insulation 2, Very High Efficacy LED Lighting	761	$593	1.8	($471)	$710	$450
12	Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heaters, Exterior Wall Insulation, Very High Efficacy LED Lighting	725	$566	1.7	($417)	$653	$473
13	Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heaters, Exterior Wall Insulation, Very High Efficacy LED Lighting	614	$446	2.4	($628)	$482	$419
14	Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heaters, Exterior Wall Insulation, Very High Efficacy LED Lighting	729	$575	1.8	($483)	$2,728	$478

15	Evaporative Pre-Cooling of Condenser and Ventilation Air, Heat Pump Water Heaters, Exterior Wall Insulation 2, Very High Efficacy LED Lighting	700	$529	2.2	($654)	$2,576	$425
16	Heat Pump Water Heaters, Exterior Wall Insulation, High Efficacy LED Lighting	644	$441	2.2	($551)	$539	$383

Source: University of California, Davis

Table 28: Summary of Results – Efficiency + PV

CZ	Most cost-effective package if using roof mounted PV with optimum tilt to reach ZNE-TDV	PV Capacity (kW DC at STC)	Total Upgrade Cost ($1000s)	TDV$/$ for PV ZNE Package	Societal Cost (upgrade + change in TDV $1000s)	Builder Owner Cost (upgrade + change in Utility NPV $1000s)	Upgrade cost $ per tonne 30 yr. CO_2e reduction
1	Heat Pump Water Heaters, High Efficacy LED Lighting	170	$360	2.4	($517)	($277)	$1,299
2	Heat Pump Water Heaters, Exterior Wall Insulation, High Efficacy LED Lighting	138	$297	3.3	($697)	($483)	$768
3	Heat Pump Water Heaters, Exterior Wall Insulation, High Efficacy LED Lighting	122	$263	3.3	($599)	($442)	$763
4	Heat Pump Water Heaters, Exterior Wall Insulation, High Efficacy LED Lighting	119	$256	3.7	($704)	($524)	$725
5	Heat Pump Water Heaters, Exterior Wall Insulation, High Efficacy LED Lighting	111	$243	3.4	($585)	($466)	$691

6	Heat Pump Water Heaters, Exterior Wall Insulation, High Efficacy LED Lighting	109	$239	3.7	($643)	($238)	$664
7	Heat Pump Water Heaters, Exterior Wall Insulation, Very High Efficacy LED Lighting	110	$246	3.3	($577)	($357)	$670
8	Heat Pump Water Heaters, Exterior Wall Insulation, High Efficacy LED Lighting	108	$232	4.2	($752)	($288)	$616
9	Heat Pump Water Heaters, Exterior Wall Insulation, High Efficacy LED Lighting	112	$238	4.2	($769)	($288)	$609
10	Heat Pump Water Heaters, Exterior Wall Insulation, High Efficacy LED Lighting	117	$248	4.1	($768)	($590)	$600
11	Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heaters, High Efficacy LED Lighting	146	$321	3.3	($744)	($539)	$931
12	Heat Pump Water Heaters, High Efficacy LED Lighting	141	$301	3.3	($682)	($507)	$952
13	Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heaters, High Efficacy LED Lighting	142	$314	3.4	($760)	($552)	$890
14	Heat Pump Water Heaters, High Efficacy LED Lighting	120	$255	4.2	($803)	($266)	$700

15	Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heaters, Exterior Wall Insulation, High Efficacy LED Lighting	118	$293	4.0	($891)	($524)	$594
16	Heat Pump Water Heaters, High Efficacy LED Lighting	144	$303	3.3	($688)	($494)	$940

Source: University of California, Davis

Results Discussion: Retail Standalone

Heavy Mass Walls

The Retail Standalone building type uses heavy mass walls as recommended as typical California construction practice (Skanska, 2019). Title 24 building codes allow relatively low baseline levels of wall insulation for heavy mass walls in CZ 2-10, so upgrading exterior wall insulation levels is TDV cost-effective. In cooling dominated climates heavy mass walls absorb heat throughout the day leading to higher cooling energy consumption in the late afternoon and evening hours which have now become peak times of grid stress and peak TDV factor values. For building types with schedules that have active cooling in the late afternoon and evening and in climate zones where outdoor temperatures remain high in the late afternoon and evening, additional wall insulation is cost-effective. If buildings have schedules that turn off cooling systems after 5pm and or they are in climate zones where a large drop in outside air temperature allows economizer "free cooling" then the value of additional insulation will be lower. A significant factor in wall insulation cost-effectiveness is the reduced size of cooling systems to meet design day requirements. The cost reduction from reducing cooling system size can offset a portion of the added wall insulation costs. For Retail Standalone climate zones 2, 5, 7, and 10 the reduction in cooling system sizing from additional wall insulation level 1 more than pays for the additional insulation so that the total construction cost is reduced. This suggests that stricter building codes could reduce construction costs and societal costs in mild climate zones. Also, in climate zones 8 and 9 the HVAC size and cost reductions almost completely pay for the additional wall insulation level 1. This analysis is sensitive to the size steps in insulation upgrades and to the building schedules in ways that interact with the climate zone, so even more detailed analysis may allow for even more granular optimum selection of the amount of additional insulation.

Utility Bill Analysis

The additional construction cost for upgrades was added to the change in the 30-year net present value of the utility bills at a 5 percent discount rate to calculate the builder or owner total cost net present value. For efficiency plus PV packages in all climate zones the utility bills are reduced enough to more than pay back the additional construction cost of upgrades so that there was a net savings to the builder or owner. For efficiency plus battery packages the utility bills were reduced in climate zones 6-9 but not reduced enough from the baseline to pay back the additional construction costs so that there was a net cost to the builder or owner. For efficiency plus battery packages the utility bills were increased in climate zones 1-5 and 10-16 so that the net cost to the builder or owner was even larger than the additional construction cost.

Priorities for Future Work: Retail Standalone

Future work for the standalone retail building type could include:

- Cooling HVAC downsizing for – Evaporative pre-cooling (CoilCool and DualCool)
- Ceiling Fans
- Skylights for non-energy benefits

Building Type: Multitenant Light Commercial

Applicable Upgrade Measures

The following summarizes the non-HVAC energy conservation upgrade measures applicable to the warehouse:

- Photovoltaic Panels – Rooftop optimum tilt
- Battery Storage
- Domestic Hot Water Heating Equipment
    - ➢ Electric heat pump storage tank water heaters
    - ➢ Natural gas fueled storage tank water heaters
    - ➢ Natural gas fueled condensing storage tank water heaters
    - ➢ Natural gas fueled tankless water heaters
- High Efficiency Lighting Technology – Upgrade troffers from linear fluorescent to LED and LED baseline for task and accent lighting, second level upgrade to very high effectiveness LED troffers
- Daylighting and Occupancy Lighting Controls
- Increased Wall and Roof Insulation
- Aerosol Envelope Sealing (Aerobarrier)
- Exterior window overhangs
- Cool Roof
- Fenestration
    - ➢ High Performance Windows – additional room side Low-E coating and or frame thermal break
    - ➢ Skylights replacing baseline Light Tubes
- Blinds and Shades
- Thermal Mass - increase concrete slab floor thickness

The applicable HVAC upgrade measures modeled are:

- RTU evaporative condenser air pre-cooling and ventilation air pre-cooling (ICI DualCool)
- RTU evaporative condenser air pre-cooling (ICI CoilCool)
- Increased RTU COP, variable speed supply fan, variable speed condenser
- RTU heat pumps for heating

The following summarizes the results of the two-step process designed to determine the most cost-effective technology packages.

Individually Cost-Effective Measures

The following energy conservation measures were found to be TDV cost-effective, specifically to have a TDV dollar savings divided by dollar additional construction cost to calculate TDV return on investment TDV$/$ greater than one in one or more climate zones. Measures are listed in rough order of largest TDV$/$ return on investment across climate zones.

- High Efficiency Lighting Technology – Upgrade troffers from linear fluorescent to LED and LED baseline for task and accent lighting, second level upgrade to very high effectiveness LED troffers
- RTU evaporative condenser air pre-cooling and ventilation air pre-cooling (ICI DualCool)
- Domestic Hot Water Heating Equipment: Electric Heat Pump storage tank water heaters
- Additional Daylighting and Occupancy Lighting Controls
- Increased RTU COP with variable speed supply fan

- RTU heat pumps for heating
- RTU evaporative condenser air pre-cooling (ICI CoilCool)

Domestic Hot Water Heating Equipment (natural gas storage tank water heaters) is individually cost-effective with TDV$/$ larger than one in one or more climate zones but less than both PV and Battery systems in all climate zones so that they were not simulated in the full matrix of interacting measures.

The measures that achieve a TDV$/$ larger than either PV or Battery systems in one or more climate zones were then simulated in all possible combinations with interactions between all measures' energy savings and construction cost to find the most TDV cost-effective package of measures in each climate zone. For packages TDV cost-effective is defined as the societal cost calculated by adding the change in construction cost and the change in TDV dollars where the selected package achieves the largest total savings.

Cost-Effective Combinations of Measures

The upgrades that were found to have largest societal cost savings defined as the change in construction cost minus the TDV dollar savings were included in the best performing packages. The packages include upgrades that reduce construction costs and or have a larger TDV dollar saved per dollar additional construction cost than both PV and batteries in all climate zones are:

- High or Very High Efficacy LED Lighting – Troffers
- The following upgrades were more cost-effective than PV in the specific climate zones listed.
- Evaporative pre-cooling of condenser air and indirect evaporative pre-cooling of ventilation air in CZ 15
- The following upgrades were more cost-effective than batteries in the specific climate zones listed.
- Evaporative pre-cooling of condenser air and indirect evaporative pre-cooling of ventilation air in the two large stores in CZ 2, 10, 12-13 and for both small and large stores in climate zones 11, 14, and 15
- Heat pump RTU in climate zones 2, 11, and 12
- Very high efficacy LED troffers pay of better than high efficacy LED troffers in climate zone 10

Table 29 provides a summary of results for efficiency and battery upgrades, and Table 30 shows a summary of the results for efficiency and solar upgrades.

Table 29: Summary of Results – Efficiency + Battery

CZ	Most cost-effective package if using Battery Energy Storage to reach ZNE-TDV	Battery Capacity (kW and kWh)	Total upgrade cost $1000s	TDV$/$ for Battery ZNE Package	Societal Cost (upgrade + change in TDV $1000s)	Builder Owner Cost (upgrade + change in Utility NPV $1000s)	Upgrade $ per tonne 30 yr. CO_2e reduction
1	High Efficacy LED Lighting	503	$355	2.0	$(344)	$(141)	$488
2	Large Stores Evaporative Pre-Cooling of Condenser Air and Ventilation Air, Heat Pump RTU, Heat Pump Water Heaters, High Efficacy LED Lighting	501	$386	1.9	$(342)	$(178)	$377
3	Heat Pump Water Heaters, High Efficacy LED Lighting	501	$344	1.8	$(283)	$(164)	$447
4	Heat Pump Water Heaters, High Efficacy LED Lighting	506	$344	2.0	$(336)	$(219)	$437
5	High Efficacy LED Lighting	401	$292	2.0	$(301)	$(219)	$471
6	Heat Pump Water Heaters, High Efficacy LED Lighting	466	$348	1.8	$(279)	$109	$480
7	High Efficacy LED Lighting	369	$251	2.3	$(326)	$(58)	$427

8	Heat Pump Water Heaters, High Efficacy LED Lighting	504	$371	1.9	$(334)	$105	$472
9	High Efficacy LED Lighting	440	$294	2.5	$(433)	$20	$423
10	Large Stores Evaporative Pre-Cooling of Condenser Air and Ventilation Air, Heat Pump Water Heaters, Very High Efficacy LED Lighting	656	$500	1.5	$(242)	$212	$491
11	Small and Large Stores Evaporative Pre-Cooling of Condenser Air and Ventilation Air, Heat Pump RTU, Heat Pump Water Heaters, High Efficacy LED Lighting	585	$494	1.7	$(335)	$(43)	$428
12	Large Stores Evaporative Pre-Cooling of Condenser Air and Ventilation Air, Heat Pump RTU, Heat Pump Water Heaters, High Efficacy LED Lighting	587	$459	1.7	$(307)	$(167)	$410
13	Large Stores Evaporative Pre-Cooling of Condenser Air and Ventilation Air, High Efficacy LED Lighting	545	$365	2.3	$(471)	$(329)	$431
14	Small and Large Stores Evaporative Pre-Cooling of Condenser Air and Ventilation Air, Heat Pump Water Heaters, High Efficacy LED Lighting	562	$461	1.7	$(345)	$177	$524

15	Small and Large Stores Evaporative Pre-Cooling of Condenser Air and Ventilation Air, Heat Pump Water Heaters, High Efficacy LED Lighting	605	$448	2.1	$(482)	$77	$447
16	High Efficacy LED Lighting	535	$347	2.1	$(395)	$(199)	$434

Source: University of California, Davis

Table 30: Summary of Results – Efficiency + PV

CZ	Most cost-effective package if using Efficiency + PV to reach ZNE-TDV	PV Capacity (kW and kWh)	Total upgrade cost $1000s	TDV$/$ for Battery ZNE Package	Societal Cost (upgrade + change in TDV $1000s)	Builder Owner Cost (upgrade + change in Utility NPV $1000s)	Upgrade $ per tonne 30 yr. CO_2e reduction
1	High Efficacy LED Lighting	138	$297	2.4	$(402)	$617	$1,398
2	High Efficacy LED Lighting	107	$232	3.1	$(496)	$537	$996
3	High Efficacy LED Lighting	94	$207	3.0	$(420)	$511	$983
4	High Efficacy LED Lighting	91	$200	3.4	$(480)	$505	$894
5	High Efficacy LED Lighting	83	$185	3.2	$(408)	$467	$849

6	High Efficacy LED Lighting	81	$181	3.5	$(447)	$97	$740
7	High Efficacy LED Lighting	82	$183	3.1	$(394)	$674	$756
8	High Efficacy LED Lighting	84	$186	3.8	$(519)	$101	$734
9	High Efficacy LED Lighting	87	$193	3.8	$(534)	$122	$736
10	High Efficacy LED Lighting	92	$203	3.7	$(539)	$95	$732
11	High Efficacy LED Lighting	123	$262	3.2	$(567)	$343	$971
12	High Efficacy LED Lighting	111	$241	3.2	$(525)	$568	$961
13	High Efficacy LED Lighting	119	$255	3.3	$(581)	$566	$920
14	High Efficacy LED Lighting	93	$205	3.9	$(602)	$61	$723

15	Large Stores Evaporative Pre-Cooling of Condenser Air and Ventilation Air, High Efficacy LED Lighting	107	$243	3.8	$(687)	$50	$683
16	High Efficacy LED Lighting	109	$237	3.1	$(504)	$569	$969

Source: University of California, Davis

Results Discussion: Multitenant Light Commercial

Evaporative pre-cooling of condenser and ventilation air has a lower cost when added to larger cooling capacity RTUs and saves more energy and TDV $ in drier hotter climate zones. This results in the large store upgrade being selected for the most societal cost-effective package in more climate zones than for the small stores.

Multiple efficiency upgrades are close to being selected in many climate zones but are slightly less cost-effective than PV or than the selected upgrade. For example, Very High Efficacy LED lighting troffers are almost as cost-effective as High Efficacy LED lighting troffers and reduce TDV more but are not selected in the optimum cost-effectiveness package.

Priorities for Future Work: Multitenant Light Commercial

Account for reduction in RTU cooling capacity required when upgrading to evaporative pre-cooling strategies.

Consider small indirect evaporative cooler integrated heat pump as full RTU replacement in the driest climate zones.

Consider Ceiling fans integrated with thermostats.

Building Type: Highrise Multifamily

Applicable Upgrade Measures

The following list summarizes the non-HVAC energy conservation upgrade measures applicable to the Highrise Multifamily:

- Photovoltaic Panels – Rooftop optimum tilt
- Battery Storage
- High Efficiency Lighting Technology – Upgrade recessed downlights and screw in lamps from compact fluorescent to LED
- Domestic Hot Water Heating Equipment
    - Electric heat pump storage tank water heaters
    - Natural gas fueled storage tank water heaters
    - Natural gas fueled condensing storage tank water heaters
    - Natural gas fueled tankless water heaters
- Additional Daylighting and Occupancy Lighting Controls
- Traction elevator regenerative drive for increased efficiency
- Increased Wall and Roof Insulation
- Aerosol Envelope Sealing (Aerobarrier)
- Cool Roof
- Fenestration
    - High Performance Windows – additional room side Low-E coating and or frame thermal break
- Blinds and Shades
- Thermal Mass - increase concrete slab floor thickness

The applicable HVAC upgrade measures modeled are:

- Chiller evaporative condenser air pre-cooling. (ICI CoilCool)

- Condensing boiler for increased efficiency heating the hot water loop supplying the fan coil units in each zone
- Large air to water Heat Pump to heat hot water loop supplying the fan coil units in each zone

The following summarizes the results of the two-step process designed to determine the most cost-effective technology packages.

Individually Cost-Effective Measures

The following energy conservation measures were found to be TDV cost-effective, specifically to have a TDV dollar savings divided by dollar additional construction cost to calculate TDV return on investment TDV$/$ greater than one in one or more climate zones. Measures are listed in rough order of largest TDV$/$ return on investment across climate zones.

- Domestic Hot Water Heating Equipment:
  - Electric Heat Pump storage tank water heaters,
  - Natural gas fueled water heaters cost-effectiveness depends on length and cost of gas piping which would require more detailed design information
- Large air to water Heat Pump to heat hot water loop supplying the fan coil units in each zone
- High Efficiency Lighting Technology – Upgrade recessed downlights and screw in lamps from compact fluorescent to LED
- Condensing boiler for increased efficiency heating the hot water loop supplying the fan coil units in each zone
- Traction elevator regenerative drive for increased efficiency
- Additional Daylighting and Occupancy Lighting Controls
- Chiller evaporative condenser air pre-cooling. (ICI CoilCool)

Upgrades listed in italic font are individually cost-effective with TDV$/$ larger than one in one or more climate zones but less than both PV and Battery systems in all climate zones so that they were not simulated in the full matrix of interacting measures.

- *Increased Wall insulation (CZ 11 and 16)*
- *Aerosol Envelope Sealing (Aerobarrier) (CZ 11 and 16)*

The measures that achieve a TDV$/$ larger than either PV or Battery systems in one or more climate zones were then simulated in all possible combinations with interactions between all measures' energy savings and construction cost to find the most TDV cost-effective package of measures in each climate zone. For packages TDV cost-effective is defined as the societal cost calculated by adding the change in construction cost and the change in TDV dollars where the selected package achieves the largest total savings.

Cost-Effective Combinations of Measures

The upgrades that were found to have largest societal cost savings defined as the change in construction cost minus the TDV dollar savings were included in the best performing packages. The selected packages include upgrades that reduce construction costs and or have a larger TDV dollar saved per dollar additional construction cost than batteries or for efficiency plus PV TDV$/$>1 in all climate zones are:

- Domestic Hot Water Heating Equipment: Electric Heat Pump storage tank water heaters

- High Efficiency Lighting Technology – Upgrade recessed downlights and screw in lamps from compact fluorescent to LED

The following upgrades were cost-effective TDV $/$ >1 and were selected as part of the efficiency plus PV package in the specific climate zones listed.

- Large air to water Heat Pump to heat hot water loop supplying the fan coil units in each space in climate zones 1-15
- Chiller evaporative condenser air pre-cooling (ICI CoilCool) in climate zones 2-4, 6, 8-15
- Additional Daylighting and Occupancy Lighting Controls in all climate zones 1-16
- Traction elevator regenerative drive for increased efficiency in all climate zones 1-16

The following upgrades were more cost-effective than batteries in the specific climate zones listed.

- Large air to water Heat Pump to heat hot water loop supplying the fan coil units in each space in climate zones 1-15
- Chiller evaporative condenser air pre-cooling (ICI CoilCool) in climate zones 2-4, 6, 8-15
- Additional Daylighting and Occupancy Lighting Controls in climate zones 2-6, 8, 10-12, 14-15
- Traction elevator regenerative drive for increased efficiency in climate zone 10.

Table 31 provides a summary of results for efficiency and battery upgrades, and Table 32 shows a summary of the results for efficiency and solar upgrades.

Table 31: Summary of Results – Efficiency + Battery

CZ	Most cost-effective package if using Battery Energy Storage to reach ZNE-TDV	Battery Capacity (kW and kWh)	Total upgrade cost $1000s	TDV$/$ for Battery ZNE Package	Societal Cost (upgrade + change in TDV $1000s)	Builder Owner Cost (upgrade + change in Utility NPV $1000s)	Upgrade $ per tonne 30 yr. CO_2e reduction
1	Hot Water Loop Heat Pump, Heat Pump Water Heater, LED Lighting	1560	$1,067	2.9	$(2,017)	$877	$279
2	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heater, Lighting Controls, LED Lighting	1872	$1,297	2.6	$(2,037)	$1,055	$321
3	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heater, Lighting Controls, LED Lighting	1888	$1,239	2.6	$(1,938)	$975	$307
4	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heater, Lighting Controls, LED Lighting	1939	$1,259	2.7	$(2,150)	$996	$313
5	Hot Water Loop Heat Pump, Heat Pump Water Heater, Lighting Controls, LED Lighting	1555	$1,105	2.8	$(2,036)	$771	$316
6	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling,	1979	$1,406	2.4	$(1,952)	$143,158	$357

	Heat Pump Water Heater, Lighting Controls, LED Lighting						
7	Hot Water Loop Heat Pump, Heat Pump Water Heater, LED Lighting	1677	$1,079	3.1	$(2,244)	$1,883	$308
8	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heater, Lighting Controls, LED Lighting	1962	$1,382	2.5	$(2,105)	$143,227	$352
9	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heater, LED Lighting	1620	$1,041	3.4	$(2,448)	$142,703	$298
10	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Regenerative Elevator Drive, Heat Pump Water Heater, Lighting Controls, LED Lighting	2577	$1,823	1.9	$(1,721)	$144,051	$376
11	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heater, Lighting Controls, LED Lighting	2357	$1,677	2.2	$(2,040)	$1,570	$348
12	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heater, Lighting Controls, LED Lighting	2219	$1,573	2.3	$(1,972)	$1,389	$346

13	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heater, LED Lighting	1930	$1,221	3.1	$(2,531)	$978	$298
14	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heater, Lighting Controls, LED Lighting	2210	$1,588	2.3	$(2,020)	$2,144	$358
15	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Heat Pump Water Heater, Lighting Controls, LED Lighting	2518	$1,605	2.5	$(2,468)	$2,168	$333
16	Condensing Boiler, Heat Pump Water Heater, LED Lighting	2048	$1,280	2.7	$(2,158)	$1,288	$324

Source: University of California, Davis

Table 32: Summary of Results – Efficiency + PV

CZ	Most cost-effective package if using roof mounted PV with optimum tilt to reach ZNE-TDV	PV Capacity (kW DC at STC)	Total Upgrade Cost ($1000s)	TDV Reduction	TDV$/$ for PV ZNE Package	Societal Cost (upgrade + change in TDV $1000s)	Builder Owner Cost (upgrade + change in Utility NPV $1000s)	Upgrade cost $ per tonne 30 yr. CO_2e reduction
1	Hot Water Loop Heat Pump, Regenerative Elevator Drive, Heat Pump Water Heater, Lighting Controls, LED Lighting	11	$299	39%	3.8	$(842)	$(90)	$184
2	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Regenerative Elevator Drive,	11	$300	38%	3.9	$(859)	$(305)	$220

	Heat Pump Water Heater, Lighting Controls, LED Lighting							
3	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Regenerative Elevator Drive, Heat Pump Water Heater, Lighting Controls, LED Lighting	11	$297	39%	3.9	$(861)	$(404)	$224
4	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Regenerative Elevator Drive, Heat Pump Water Heater, Lighting Controls, LED Lighting	11	$297	38%	3.9	$(874)	$(389)	$235
5	Hot Water Loop Heat Pump, Regenerative Elevator Drive, Heat Pump Water Heater, Lighting Controls, LED Lighting	11	$298	39%	3.8	$(835)	$(427)	$235
6	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Regenerative Elevator Drive, Heat Pump Water Heater, Lighting Controls, LED Lighting	11	$294	37%	3.8	$(832)	$(247)	$250
7	Hot Water Loop Heat Pump, Regenerative Elevator Drive, Heat Pump Water Heater, Lighting Controls, LED Lighting	11	$294	37%	3.8	$(833)	$(566)	$251
8	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Regenerative Elevator Drive,	11	$295	37%	3.9	$(856)	$(230)	$250

	Heat Pump Water Heater, Lighting Controls, LED Lighting							
9	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Regenerative Elevator Drive, Heat Pump Water Heater, Lighting Controls, LED Lighting	11	$295	37%	4.0	$(875)	$(255)	$244
10	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Regenerative Elevator Drive, Heat Pump Water Heater, Lighting Controls, LED Lighting	11	$296	36%	3.9	$(873)	$(214)	$241
11	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Regenerative Elevator Drive, Heat Pump Water Heater, Lighting Controls, LED Lighting	11	$300	36%	4.1	$(945)	$(185)	$205
12	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Regenerative Elevator Drive, Heat Pump Water Heater, Lighting Controls, LED Lighting	11	$299	37%	4.0	$(910)	$(311)	$214
13	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Regenerative Elevator Drive, Heat Pump Water Heater, Lighting Controls, LED Lighting	11	$298	36%	4.1	$(940)	$(285)	$216

14	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Regenerative Elevator Drive, Heat Pump Water Heater, Lighting Controls, LED Lighting	11	$301	36%	3.9	$(881)	$(141,490)	$222
15	Hot Water Loop Heat Pump, Chiller Evaporative Condenser Air Pre-Cooling, Regenerative Elevator Drive, Heat Pump Water Heater, Lighting Controls, LED Lighting	11	$295	36%	4.5	$(1,038)	$(141,546)	$233
16	Condensing Boiler, Regenerative Elevator Drive, Heat Pump Water Heater, Lighting Controls, LED Lighting	11	$297	29%	3.0	$(594)	$(84)	$287

Source: University of California, Davis

Results Discussion: Highrise Multifamily

The different TDV factor shapes in different climate zones have a significant impact on the size battery and, therefore, additional construction cost required to achieve ZNE-TDV.

The percent reduction in total TDV from the baseline to the selected efficiency plus PV packages ranged from 29 percent to 39 percent across climate zones.

Ventilation was provided by balanced ventilation with local exhaust and supply for each zone instead of a central ventilation system to align with current design practice. These local ventilation systems are very small compared to central ventilation systems and therefore do not have cost effective ventilation air precooling options and have reduced benefits from duct sealing so those were not considered.

Apartment unit domestic hot water heating was served by in unit 50-gallon equivalent hot water heating equipment. Heat pump storage tank water heaters are TDV cost-effective in all climate zones. Natural gas fueled storage tank water heaters increase CO_2e emissions and are either more or less TDV cost-effective than the heat pump option depending on the length and cost of the associated natural gas piping and exhaust systems. This study picked the heat pump storage tank water heaters because they are both TDV cost-effective and also reduce CO_2e emissions.

Priorities for Future Work: Highrise Multifamily

Consider Ceiling fans integrated with thermostats.

Building Type: Full-Service Restaurant

Applicable Upgrade Measures

The following list summarizes the non-HVAC energy conservation upgrade measures applicable to the warehouse:

- Photovoltaic Panels – 80 percent of south facing side of rooftop with optimum tilt
- Battery Storage
- High Efficiency Lighting Technology – Upgrade troffers from linear fluorescent to second level upgrade of very high efficacy LED 150 lumens per watt in kitchen, recessed downlighting from CFL to high efficacy LED 90 lumens per watt in kitchen and dining room, and screw in lamps from CFL to high efficacy LED 94 lumens per watt in the dining room
- Additional Daylighting and Occupancy Lighting Controls
- Increased Wall and Roof Insulation
- Aerosol Envelope Sealing (Aerobarrier)
- Cool Roof
- Fenestration
    - High Performance Windows – additional room side Low-E coating and or frame thermal break
    - Skylights replacing baseline Light Tubes
- Blinds and Shades
- Thermal Mass - increase concrete slab floor thickness

The applicable HVAC upgrade measures modeled are:

- RTU evaporative condenser air pre-cooling and ventilation air pre-cooling (ICI DualCool)

- RTU evaporative condenser air pre-cooling (ICI CoilCool)
- Increased RTU COP, variable speed supply fan, variable speed condenser
- RTU heat pumps for heating

What follows summarizes the results of the two-step process designed to determine the most cost-effective technology packages.

Individually Cost-Effective Measures

The following energy conservation measures were found to be TDV cost-effective, specifically to have a TDV dollar savings divided by dollar additional construction cost to calculate TDV return on investment TDV$/$ greater than one in one or more climate zones. Measures are listed in rough order of largest TDV$/$ return on investment across climate zones.

- High Efficiency Lighting Technology – Upgrade troffers from linear fluorescent to second level upgrade of very high efficacy LED 150 lumens per watt in kitchen, recessed downlighting from CFL to high efficacy LED 90 lumens per watt in kitchen and dining room, and screw in lamps from CFL to high efficacy LED 94 lumens per watt in the dining room
- Additional ceiling insulation
- RTU evaporative condenser air pre-cooling and ventilation air pre-cooling (ICI DualCool)
- RTU evaporative condenser air pre-cooling (ICI CoilCool)
- RTU heat pumps for heating
- Increased RTU COP, variable speed supply fan
- Additional Daylighting and Occupancy Lighting Controls
- Increased RTU COP, variable speed supply fan, and variable speed condenser

The measures that achieve a TDV$/$ larger than one in one or more climate zones were then simulated in all possible combinations with interactions between all measures' energy savings and construction cost to find the most TDV cost-effective package of measures in each climate zone. For packages TDV cost-effective is defined as the societal cost calculated by adding the change in construction cost and the change in TDV dollars where the selected package achieves the largest total savings.

Cost-Effective Combinations of Measures

The upgrades that were found to have largest societal cost savings defined as the change in construction cost minus the TDV dollar savings were included in the best performing packages. The packages include upgrades that reduce construction costs and or have a larger TDV dollar saved per dollar additional construction cost than both PV and batteries in all climate zones are:

- High or Very High Efficacy LED Lighting – Upgrade troffers from linear fluorescent to second level upgrade of very high efficacy LED 150 lumens per watt in kitchen, recessed downlighting from CFL to high efficacy LED 90 lumens per watt in kitchen and dining room, and screw in lamps from CFL to high efficacy LED 94 lumens per watt in the dining room
- Additional ceiling insulation – Blown in fiberglass above the tops of the ceiling joists

The following upgrades were more cost-effective than batteries in the specific climate zones listed.

- RTU heat pumps for heating in climate zones 1-3, and 5

- Evaporative pre-cooling of condenser air and indirect evaporative pre-cooling of ventilation air in climate zones 4, and 5-15

The following upgrades achieved a TDV$/$ greater than one and were included in the PV packages in the specific climate zones listed.

- RTU heat pumps for heating in climate zones 1-3, and 5
- Evaporative pre-cooling of condenser air and indirect evaporative pre-cooling of ventilation air in CZ 4, and 5-16
- Additional daylighting and occupancy lighting controls in climate zones 2, 7-11, 13, and 15.

Table 33 provides a summary of results for efficiency and battery upgrades, and Table 34 shows a summary of the results for efficiency and solar upgrades.

Table 33: Summary of Results – Efficiency + Battery

CZ	Most cost-effective package if using Battery Energy Storage to reach ZNE-TDV	Battery Capacity (kW and kWh)	Total upgrade cost $1000s	TDV$/$ for Battery ZNE Package	Societal Cost (upgrade + change in TDV $1000s)	Builder Owner Cost (upgrade + change in Utility NPV $1000s)	Upgrade $ per tonne 30 yr. CO_2e reduction
1	RTU Heat Pumps, Ceiling Insulation, LED Lighting	1447	$999	2.0	$(1,014)	$1,474	$261
2	RTU Heat Pumps, Ceiling Insulation, LED Lighting	1606	$1,097	1.9	$(944)	$1,530	$323
3	RTU Heat Pumps, Ceiling Insulation, LED Lighting	1540	$1,000	1.8	$(788)	$1,442	$327
4	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1536	$973	2.0	$(932)	$1,290	$423
5	RTU Heat Pumps, Ceiling Insulation, LED Lighting	1275	$893	2.0	$(874)	$1,235	$332
6	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1410	$984	1.7	$(698)	$3,404	$481
7	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1128	$723	2.2	$(849)	$835	$435

8	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1398	$966	1.9	$(842)	$3,429	$469
9	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1174	$750	2.5	$(1,121)	$3,066	$416
10	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1922	$1,339	1.5	$(606)	$4,095	$472
11	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1859	$1,296	1.7	$(886)	$1,633	$460
12	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1811	$1,257	1.7	$(822)	$1,614	$464
13	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1475	$925	2.4	$(1,253)	$1,158	$406
14	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1750	$1,230	1.7	$(914)	$3,722	$471
15	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1725	$1,081	2.1	$(1,140)	$3,508	$407

16	Ceiling Insulation, LED Lighting	1600	$983	2.1	$(1,101)	$1,398	$402

Source: University of California, Davis

Table 34: Summary of Results – Efficiency + PV

CZ	Most cost-effective package if using roof mounted PV with optimum tilt to reach ZNE-TDV	PV Capacity (kW DC at STC)	Total Upgrade Cost ($1000s)	TDV Reduction	TDV$/$ for PV ZNE Package	Societal Cost (upgrade + change in TDV $1000s)	Builder Owner Cost (upgrade + change in Utility NPV $1000s)	Upgrade cost $ per tonne 30 yr. CO_2e reduction
1	RTU Heat Pumps, Ceiling Insulation, LED Lighting	3.2	$109	17%	3.2	$(234)	$43	$62
2	RTU Heat Pumps, Ceiling Insulation, Lighting Controls, LED Lighting	3.2	$113	20%	3.6	$(290)	$(63)	$102
3	RTU Heat Pumps, Ceiling Insulation, LED Lighting	3.2	$101	20%	3.5	$(249)	$(51)	$119
4	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	3.2	$86	19%	4.3	$(282)	$(213)	$794
5	RTU Heat Pumps, Ceiling Insulation, LED Lighting	3.2	$99	19%	3.4	$(242)	$(87)	$115
6	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	3.2	$86	20%	3.8	$(245)	$(92)	$1,182

7	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, Lighting Controls, LED Lighting	3.2	$100	19%	2.9	$(193)	$(156)	$1,345
8	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, Lighting Controls, LED Lighting	3.2	$99	23%	4.2	$(320)	$(123)	$871
9	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, Lighting Controls, LED Lighting	3.2	$99	23%	4.4	$(336)	$(125)	$782
10	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, Lighting Controls, LED Lighting	3.2	$99	23%	4.4	$(341)	$(136)	$693
11	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, Lighting Controls, LED Lighting	3.2	$98	21%	4.7	$(365)	$(269)	$532
12	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	3.2	$86	19%	4.6	$(305)	$(239)	$601
13	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, Lighting Controls, LED Lighting	3.2	$99	21%	4.7	$(365)	$(269)	$539
14	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	3.2	$86	23%	5.8	$(414)	$(158)	$503
15	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, Lighting Controls, LED Lighting	3.2	$98	28%	6.3	$(519)	$(212)	$426

16	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	3.2	$86	15%	3.6	$(218)	$(151)	$538

Source: University of California, Davis

Results Discussion: Full-Service Restaurant

For the full-service restaurant building type the PV panels were assumed to be at the optimum angle on the 80 percent available area of the south facing half of the sloped roof. This resulted in a PV system output of 3.2 kW (DC STC) which was not sufficient to reach ZNE-TDV in any climate zone. The TDV percent reduction from the baseline to the upgrade cost-effective efficiency plus PV packages ranged from 15 percent to 28 percent. Future work can consider the additional costs to change the roof to a shed roof style with a full width slope towards the south at the optimum PV tilt angle to reach 80 percent of the whole roof area available for PV. Even with PV covering 80 percent of the whole roof area the upgrade to cost-effective efficiency plus PV packages will not reach ZNE-TDV so the efficiency measures selected would not be expected to change.

In climate zone one, the efficiency plus PV package reduced utility bills but not by enough for the 30-year net present value to pay for the additional construction cost for the upgrades so that builder owner cost increases compared to the baseline. Part of the smaller reduction in utility bills is the switch from lower utility costs natural gas furnace heating to higher electric heat pump heating. In addition, the upgrade to heat pump heating may lead to higher electric demand power (kW) which would increase utility demand charges and could push the building onto a more expensive tariff. Part of the larger construction cost is that in climate zone one there are very low cooling and high heating requirements so that upgrading to heat pump heating required a significantly larger and, therefore, more expensive roof top units compared to baseline air conditioning with gas furnace. The large number of heating degree days in climate zone one leads to a large CO_2e savings for the roof top unit heat pumps so that cost per tonne CO_2e saved is low compared to other climate zones where the heat pump upgrade is not selected. In all climate zones, other than climate zone one, the efficiency plus PV package results in reduced net present value builder owner costs. In climate zones 2, 3, and 5 the large number of heating degree days combined with smaller difference in sizing for the baseline roof top unit compared to the heat pump upgrade allow the roof top unit heat pumps to pay back their upgrade costs and achieve builder owner net present value cost reductions compared to baseline.

Additional ceiling insulation is blown in fiberglass that is inexpensive. Because insulation required by Title 24 is at a depth that covers the tops of the ceiling joists the upgrade additional depth of insulation added is entirely above the height of the joists so that it has no thermal bridging and the actual additional R-value is the same as the nominal material R-value. The low cost and significant energy savings make the additional ceiling insulation cost-effective in all climate zones. These results would be relevant for designs that place ducts in conditioned space since the current models do not include duct heat transfer or duct leakage. Typical practice places ducts in the attic space where duct heat transfer and air leakage can change the attic space temperature and reduce the benefits of additional ceiling insulation. Future work could consider duct placement options and interactions with HVAC and insulation.

Conversations with the Food Service Technology Center identified issues with the ways that exhaust hood and outdoor air flows are modeled in EnergyPlus. Addressing these issues was beyond the scope of this broad study. The cost effectiveness of evaporative pre-cooling of condenser and ventilation air will depend on whether the outside air flows required to replace the exhaust flows are conditioned by the kitchen RTU, transfer air from the dining RTU, a separate make up air unit, or an unconditioned or only evaporatively cooled air supply. Overall, the impact of correcting these modelling limitations are expected to make evaporative cooling upgrades marginally more cost-effective.

Priorities for Future Work: Full-Service Restaurant

- EnergyPlus development to more accurately account for outside and exhaust air flows for real restaurant buildings.
- Add modelling of air duct heat transfer and leakage along with options to place ducts in conditioned space, deeply burry ducts in ceiling insulation, additional duct insulation, and duct sealing.
- Consider demand-controlled kitchen ventilation upgrades and interactions with HVAC energy consumption.
- Account for reduction in RTU cooling capacity required when upgrading to evaporative pre-cooling strategies.
- Consider small indirect evaporative cooler for pre-cooling Ventilation air in the warmer and drier climate zones.
- Consider ceiling fans integrated with thermostats.
- Consider cooking appliance electrification and refrigeration equipment upgrades.

Building Type: Quick Service Restaurant

Applicable Upgrade Measures

The following list summarizes the non-HVAC energy conservation upgrade measures applicable to the warehouse:

- Photovoltaic Panels – 80 percent of south facing side of rooftop with optimum tilt
- Battery Storage
- High Efficiency Lighting Technology – Upgrade troffers from linear fluorescent to second level upgrade of very high efficacy LED 150 lumens per watt in kitchen, recessed downlighting from CFL to high efficacy LED 90 lumens per watt in kitchen and dining room, and screw in lamps from CFL to high efficacy LED 94 lumens per watt in the dining room
- Additional Daylighting and Occupancy Lighting Controls
- Increased Wall and Roof Insulation
- Aerosol Envelope Sealing (Aerobarrier)
- Cool Roof
- Fenestration
    - High Performance Windows – additional room side Low-E coating and or frame thermal break
    - Skylights replacing baseline Light Tubes
- Blinds and Shades
- Thermal Mass - increase concrete slab floor thickness

The applicable HVAC upgrade measures modeled are:

- RTU evaporative condenser air pre-cooling and ventilation air pre-cooling (ICI DualCool)
- RTU evaporative condenser air pre-cooling (ICI CoilCool)
- Increased RTU COP, variable speed supply fan, variable speed condenser

- RTU heat pumps for heating

What follows summarizes the results of the two-step process designed to determine the most cost-effective technology packages.

Individually Cost-Effective Measures

The following energy conservation measures were found to be TDV cost-effective, i.e. to have a TDV dollar savings divided by dollar additional construction cost to calculate TDV return on investment TDV$/$ greater than one in one or more climate zones. Measures are listed in rough order of largest TDV$/$ return on investment across climate zones.

- High Efficiency Lighting Technology – Upgrade troffers from linear fluorescent to second level upgrade of very high efficacy LED 150 lumens per watt in kitchen, recessed downlighting from CFL to high efficacy LED 90 lumens per watt in kitchen and dining room, and screw in lamps from CFL to high efficacy LED 94 lumens per watt in the dining room.
- Additional ceiling insulation
- RTU evaporative condenser air pre-cooling and ventilation air pre-cooling (ICI DualCool)
- RTU evaporative condenser air pre-cooling (ICI CoilCool)
- RTU heat pumps for heating
- Increased RTU COP, variable speed supply fan
- Additional Daylighting and Occupancy Lighting Controls
- Increased RTU COP, variable speed supply fan, and variable speed condenser

Upgrades listed in italic font are individually cost-effective with TDV$/$ larger than one in one or more climate zones but less than both PV and Battery systems in all climate zones so that they were simulated in the full matrix of interacting measures paired with PV but not with batteries.

- *High Performance Windows – additional room side Low-E coating*

The measures that achieve a TDV$/$ larger than one in one or more climate zones were then simulated in all possible combinations with interactions between all measures' energy savings and construction cost to find the most TDV cost-effective package of measures in each climate zone. For packages TDV cost-effective is defined as the societal cost calculated by adding the change in construction cost and the change in TDV dollars where the selected package achieves the largest total savings.

Cost-Effective Combinations of Measures

The upgrades that were found to have largest societal cost savings defined as the change in construction cost minus the TDV dollar savings were included in the best performing packages. The packages include upgrades that reduce construction costs and or have a larger TDV dollar saved per dollar additional construction cost than both PV and batteries in all climate zones are:

- High or Very High Efficacy LED Lighting – Upgrade troffers from linear fluorescent to second level upgrade of very high efficacy LED 150 lumens per watt in kitchen, recessed downlighting from CFL to high efficacy LED 90 lumens per watt in kitchen and dining room, and screw in lamps from CFL to high efficacy LED 94 lumens per watt in the dining room.

- Additional ceiling insulation – Blown in fiberglass above the tops of the ceiling joists

The following upgrades were more cost-effective than batteries in the specific climate zones listed.

- RTU heat pumps for heating in climate zones 1-3, and 5
- Evaporative pre-cooling of condenser air and indirect evaporative pre-cooling of ventilation air in climate zones 4, and 5-15

The following upgrades achieved a TDV$/$ greater than one and were included in the PV packages in the specific climate zones listed.

- RTU heat pumps for heating in climate zones 1-3, and 5
- Evaporative pre-cooling of condenser air and indirect evaporative pre-cooling of ventilation air in CZ 4, and 5-16
- Additional daylighting and occupancy lighting controls in climate zones 2, 7-11, and 13

Table 35 provides a summary of results for efficiency and battery upgrades, and Table 36 shows a summary of the results for efficiency and solar upgrades.

Table 35: Summary of Results – Efficiency + Battery

CZ	Most cost-effective package if using Battery Energy Storage to reach ZNE-TDV	Battery Capacity (kW and kWh)	Total upgrade cost $1000s	TDV$/$ for Battery ZNE Package	Societal Cost (upgrade + change in TDV $1000s)	Builder Owner Cost (upgrade + change in Utility NPV $1000s)	Upgrade $ per tonne 30 yr. CO_2e reduction
1	RTU Heat Pumps, Ceiling Insulation, LED Lighting	1570	$1,098.8	2.1	$(1,230)	$1,693	$187
2	RTU Heat Pumps, Ceiling Insulation, LED Lighting	1578	$1,082.6	2.0	$(1,071)	$1,566	$240
3	RTU Heat Pumps, Ceiling Insulation, LED Lighting	1463	$961.1	1.9	$(890)	$1,407	$235
4	RTU Heat Pumps, Ceiling Insulation, LED Lighting	1456	$940.9	2.0	$(971)	$1,359	$259
5	RTU Heat Pumps, Ceiling Insulation, LED Lighting	1218	$858.7	2.1	$(940)	$1,209	$234
6	RTU Heat Pumps, Ceiling Insulation, LED Lighting	1234	$880.3	1.7	$(658)	$3,259	$332
7	RTU Heat Pumps, Ceiling Insulation, LED Lighting	942	$626.4	2.2	$(774)	$769	$287

8	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1275	$882.0	1.9	$(776)	$3,269	$474
9	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1101	$703.3	2.5	$(1,065)	$2,964	$420
10	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1832	$1,276.3	1.5	$(590)	$3,960	$476
11	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1929	$1,344.7	1.7	$(936)	$1,683	$464
12	RTU Heat Pumps, Ceiling Insulation, LED Lighting	1784	$1,258.4	1.7	$(882)	$1,772	$292
13	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1492	$935.5	2.4	$(1,289)	$1,149	$408
14	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1761	$1,237.5	1.8	$(941)	$3,713	$475
15	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	1622	$1,017.9	2.1	$(1,140)	$3,357	$402
16	RTU Heat Pumps, Ceiling Insulation, LED Lighting	1606	$1,028.4	2.2	$(1,185)	$1,640	$195

Source: University of California, Davis

Table 36: Summary of Results – Efficiency + PV

CZ	Most cost-effective package if using roof mounted PV with optimum tilt to reach ZNE-TDV	PV Capacity (kW DC at STC)	Total Upgrade Cost ($1000s)	TDV Reduction	TDV$/$ for PV ZNE Package	Societal Cost (upgrade + change in TDV $1000s)	Builder Owner Cost (upgrade + change in Utility NPV $1000s)	Upgrade cost $ per tonne 30 yr. CO_2e reduction
1	RTU Heat Pumps, Ceiling Insulation, LED Lighting	2.46	$110	20%	4.2	$(354)	$174	$30
2	RTU Heat Pumps, Ceiling Insulation, LED Lighting	2.46	$87	22%	5.5	$(396)	$24	$39
3	RTU Heat Pumps, Ceiling Insulation, LED Lighting	2.46	$94	24%	4.8	$(351)	$28	$47
4	RTU Heat Pumps, Ceiling Insulation, LED Lighting	2.46	$87	21%	4.7	$(324)	$(11)	$56
5	RTU Heat Pumps, Ceiling Insulation, LED Lighting	2.46	$87	22%	4.5	$(307)	$5	$45
6	RTU Heat Pumps, Ceiling Insulation, LED Lighting	2.46	$87	21%	3.8	$(242)	$(9)	$93
7	RTU Heat Pumps, Ceiling Insulation, LED Lighting	2.46	$88	22%	3.4	$(215)	$34	$104

8	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	2.46	$68	20%	5.0	$(271)	$(139)	$891
9	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	2.46	$68	21%	5.3	$(295)	$(148)	$730
10	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	2.46	$69	20%	5.4	$(301)	$(167)	$631
11	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	2.46	$69	19%	6.2	$(354)	$(259)	$434
12	RTU Heat Pumps, Ceiling Insulation, LED Lighting	2.46	$88	20%	4.8	$(339)	$12	$49
13	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	2.46	$69	19%	6.1	$(352)	$(266)	$422
14	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	2.46	$69	21%	6.6	$(387)	$(183)	$469
15	Evaporative Precooling of Condenser and Ventilation Air, Ceiling Insulation, LED Lighting	2.46	$69	27%	8.6	$(521)	$(257)	$289
16	RTU Heat Pumps, Ceiling Insulation, LED Lighting	2.46	$101	16%	3.5	$(255)	$141	$34

Source: University of California, Davis

Results Discussion: Quick Service Restaurant

For the quick service restaurant building type the PV panels were assumed to be at the optimum angle on the 80 percent available area of the south facing half of the sloped roof. This resulted in a PV system output of 2.46 kW (DC STC) which was not sufficient to reach ZNE-TDV in any climate zone. The TDV percent reduction from the baseline to the upgrade cost-effective efficiency plus PV packages ranged from 16 percent to 27 percent. Future work can consider the additional costs to change the roof to a shed roof style with a full width slope towards the south at the optimum PV tilt angle to reach 80 percent of the whole roof area available for PV. Even with PV covering 80 percent of the whole roof area the upgrade to cost-effective efficiency plus PV packages will not reach ZNE-TDV so the efficiency measures selected would not be expected to change.

In climate zones 1 and 16, the efficiency plus PV package increases the utility bill compared to the baseline so that builder owner costs increase both for construction and for operation. For the quick service restaurant, the small roof area limits the PV system capacity to 2.46 kW (DC STC) so that there is not enough solar production to reduce the utility bill compared to the baseline. Part of the increase in utility bills is the switch from lower utility costs natural gas furnace heating to higher utility cost electric heat pump heating. In addition, the upgrade to heat pump heating may lead to higher electric demand power (kW) which would increase utility demand charges and could push the building onto a more expensive tariff. In climate zone 1 and 16 there are very low cooling and high heating requirements so that upgrading to heat pump heating required a significantly larger and therefore more expensive roof top units compared to baseline air conditioning with gas furnace. The large number of heating degree days in climate zone 1 and 16 leads to large CO_2e savings for the roof top unit heat pumps so that cost per tonne CO_2e saved is low compared to other climate zones where the heat pump upgrade is not selected.

In climate zones 2-3, 5, 7, and 12, the efficiency plus PV package reduced utility bills but not by enough for the 30-year net present value to pay for the additional construction cost for the upgrades so that builder owner cost increases compared to the baseline. Part of the smaller reduction in utility bills is the switch from lower utility costs natural gas furnace heating to higher utility cost electric heat pump heating.

In climate zones 4 and 6, the efficiency plus PV package selects a heat pump and results in reduced net present value builder owner costs. On contributing factor is that in climate zones 4 and 6 the RTU equipment price increases less when upgrading to a heat pump because compressor capacity is almost the same as for the baseline with natural gas furnace.

The following quick service restaurant discussion is the same as the full service and is repeated here for readers who might have come directly to this section.

Additional ceiling insulation is blown in fiberglass that is inexpensive. Because insulation required by Title 24 is at a depth that covers the tops of the ceiling joists the upgrade additional depth of insulation added is entirely above the height of the joists so that it has no thermal bridging and the actual additional R-value is the same as the nominal material R-value. The low cost and significant energy savings make the additional ceiling insulation cost-effective in all climate zones. These results would be relevant for designs that place ducts in conditioned space since the current models do not include duct heat transfer or duct leakage. Typical practice places ducts in the attic space where duct heat transfer and air leakage can change the attic space temperature and reduce the benefits of additional ceiling insulation. Future work could consider duct placement options and interactions with HVAC and insulation.

Conversations with the Food Service Technology Center identified issues with the ways that exhaust hood and outdoor air flows are modeled in EnergyPlus. Addressing these issues was beyond the scope of this broad study. The cost effectiveness of evaporative pre-cooling of condenser and ventilation air will depend on whether the outside air flows required to replace the exhaust flows are conditioned by the kitchen RTU, transfer air from the dining RTU, a separate make up air unit, or an unconditioned or only evaporatively cooled air supply. Overall, the effect of correcting these modelling limitations is expected to make evaporative cooling upgrades marginally more cost-effective.

Priorities for Future Work: Quick Service Restaurant

- EnergyPlus development to more accurately account for outside and exhaust air flows for real restaurant buildings.
- Add modelling of air duct heat transfer and leakage along with options to place ducts in conditioned space, deeply burry ducts in ceiling insulation, additional duct insulation, and duct sealing.
- Consider demand-controlled kitchen ventilation upgrades and interactions with HVAC energy consumption.
- Account for reduction in RTU cooling capacity required when upgrading to evaporative pre-cooling strategies.
- Consider small indirect evaporative cooler for pre-cooling Ventilation air in the warmer and drier climate zones.
- Consider ceiling fans integrated with thermostats.
- Consider cooking appliance electrification and refrigeration equipment upgrades.

CHAPTER 4: Conclusions and Recommendations

The building types investigated in this report were selected because they are predicted to have significant new construction in the coming decade and they cover the range of common building attributes that are likely to impact the feasibility of reaching ZNE cost-effectively. The types of buildings range from single-story low-rise commercial buildings, to large multi-story commercial office buildings, as well as high-rise multi-family buildings which go from large roof area down to the small roof area per square footage. The types of HVAC systems range from central built-up systems to distributed packaged units. The magnitude of internal energy consumption and waste heat generation per square foot range from very low to very high. The peak occupancy schedules range from weekday, day and late evening, to night and weekend, to significant occupancy at all times. Covering these broad ranges of building attributes does a reasonable job of spanning the key parameters affecting the ability to meet ZNE cost-effectively for a wide variety of building types.

Overall Conclusions

Achieving or Approaching ZNE-TDV

A combination of energy saving efficiency measures and battery energy storage can TDV cost-effectively reach ZNE-TDV for all building types in all climate zones if battery energy storage systems are allowed to both charge by consuming power from the grid and to export power to the grid with no constraints on battery system power or energy storage capacity.

Energy efficiency measures and photovoltaic system renewable energy generation can TDV cost-effectively reach ZNE-TDV for single story relatively low energy use intensity building types in all California climate zones using 80 percent of roof area. High-rise buildings do not have sufficient roof area to reach ZNE-TDV using TDV cost-effective efficiency plus PV systems. For example, in the Large Office building type with large data center energy consumption, cost-effective efficiency plus rooftop solar achieves a TDV reduction of 12-22 percent across climate zones.

Combinations of energy saving efficiency measures, PV systems, and battery systems would be able to TDV cost-effectively reach ZNE-TDV in all climate zones for all building types.

It is roughly 30 percent more expensive to reach ZNE-TDV in climate zone 15 than the average of all climate zones due to a combination of very high cooling energy consumption in the desert climate and the climate zone TDV factors.

Efficiency Compared to PV and Batteries

TDV Cost-Effectiveness

PV and Battery Systems

Both PV and Battery systems are TDV cost-effective in all California climate zones. The TDV return on investment, calculated by dividing the TDV saved dollar value by the increase in construction costs for PV are better than for batteries in all climate zones. The differences in the metrics between climate zones are due to interactions of TDV factor hourly shapes and weather patterns in each climate zone (Table 37).

Table 37: PV and Battery System TDV Cost Effectiveness and Cost of CO_2e Saved

	PV Systems				Battery Systems	
CZ	Tilt Mounted TDV$/$	Tilt Mounted $/30-year tonne CO_2e	Flat Mounted TDV$/$	Flat Mounted $/30-year tonne CO_2e	Adjusted 0.65 TDV$/$	Adjusted 0.65 $/30-year tonne CO_2e
1	2.31	$1,153	2.00	$1,344	1.91	$463
2	3.04	$957	2.70	$1,119	1.75	$465
3	2.94	$915	2.52	$1,098	1.70	$439
4	3.33	$892	2.98	$1,054	1.85	$437
5	3.13	$760	2.67	$951	1.90	$473
6	3.37	$707	2.90	$889	1.64	$491
7	3.01	$721	2.60	$917	2.13	$443
8	3.70	$719	3.25	$900	1.75	$486
9	3.69	$695	3.24	$880	2.33	$435
10	3.58	$687	3.14	$863	1.34	$490
11	3.07	$932	2.71	$1,113	1.52	$485
12	3.09	$968	2.78	$1,111	1.54	$484
13	3.17	$931	2.87	$1,071	2.15	$432
14	3.91	$633	3.46	$813	1.58	$497
15	3.66	$646	3.22	$829	1.76	$438
16	3.11	$817	2.62	$1,012	2.06	$424

Source: University of California, Davis

Efficiency Upgrades

The list of efficiency measures that are more cost-effective than solar or batteries is surprisingly short, likely because code requires many of the cost-effective strategies and because solar and battery systems are cost-effective competition for the remaining upgrades (Table 38). Timing of energy savings and interactions between energy efficiency upgrades can significantly change TDV cost-effectiveness of efficiency upgrades compared to an average annual energy savings analysis of individual measures.

Table 38: Energy Efficiency Upgrades Ranked by TDV Cost-Effectiveness

Efficiency Upgrade	TDV Cost-Effectiveness across building types and climate zones
LED lighting (high efficacy)	**Often Construction Cost Savings**
LED lighting (very high efficacy)	**Often more TDV cost-effective than Batteries or Solar**
Supply duct sealing	
Indirect evaporative pre-cooling of ventilation air	
Evaporative pre-cooling of condenser air	
Water heaters (heat pump, gas storage tank)	
Air to water heat pump for heating hot water circulation loops*	
Condensing boiler	
HVAC packaged units (RTU) COP increase and variable speed supply fan	**More TDV cost-effective than Batteries or Solar in select building type and climate zone combinations**
HVAC roof top packaged units heat pump and packaged terminal heat pump	
Window coating and or frame thermal break*	
Lighting controls	
Elevator regenerative drive	
Additional wall insulation	
Additional roof or ceiling insulation	
HVAC roof top packaged units variable speed compressor	**Less TDV cost-effective than Batteries or Solar in all building type and climate zone combinations**
Economizer on small HVAC roof top packaged units	
Water heaters (gas tankless, gas condensing tank)	
Skylights replacing Solar Tubes	
Aerosol envelope sealing*	
Blinds and Shades*	
Cool(er) Roof*	
Thermal mass (added concrete thickness or phase change materials)*	
Window overhangs and light shelves	

*To fairly analyze the starred efficiency upgrades would require one or more of the following: further development of Energy Plus capabilities, more granular cost estimates across an even broader range of products, and/or more detail about a particular site, building design, controls, and occupant behavior.

Source: University of California, Davis

The best energy efficiency upgrades reduce waste heat generation and therefore reduce the HVAC system size and cost required enough to fully pay for themselves so that they actually lower construction costs while also reducing TDV energy costs. Examples of these negative construction cost upgrades include, high efficacy LED lighting systems with lumens per watt of ~130 for troffer and ~145 for high bay in many building types and climate zones, and additional wall insulation for heavy mass wall buildings like Retail Standalone in climate zones 2, 5, 7, and 10.

Most energy efficiency upgrades increased construction costs. The efficiency upgrades produced TDV benefit to cost ratios that depend on upgrade, climate zone, and building type roughly ranged:

- The cost of $15 to $5,700 for efficiency upgrades that almost pay for themselves with HVAC system size reduction cost savings and had very small increases in construction cost
- 1.0 to be minimally TDV Cost-effective up to 30 for efficiency upgrades where no HVAC cost savings were considered due to limitations in EnergyPlus capabilities

A few energy efficiency upgrades are more cost-effective than PV or Batteries in multiple building type and climate zone combinations including: Very High Efficacy LED Lighting (Troffers with ~150 lumens per watt), Supply duct sealing, Indirect evaporative pre-cooling of ventilation air, Evaporative pre-cooling of condenser air, Water Heaters (Heat Pump, NG Tank), Condensing boiler, and Additional Wall insulation.

A few energy efficiency upgrades are more cost-effective than PV or Batteries in one or a couple specific building type and climate zone combinations including: Packaged Units COP increase with variable speed supply fan or conversion from NG furnace to Heat Pump (RTU and PTAC), Window coating or frame thermal break, Additional lighting controls, Elevator regenerative drive, and Additional roof insulation.

Energy efficiency investments accounted for a relatively small fraction of the investment required to reach ZNE-TDV, varying significantly with climate zone and building type:

- Standalone Retail ⇨ 5.6 percent to 20 percent when combined with solar PV, and 4.3 percent to 33 percent when combined with batteries
- Large Office ⇨ 0.06 percent to 4.9 percent when combined with batteries

Some of the most cost-effective energy efficiency upgrades reduce the HVAC system size and cost, reducing efficiency upgrade cost and reducing the apparent efficiency investment compared to PV and battery systems.

Some specific efficiency upgrades that were not estimated to be cost-effective may require a deeper level of modelling, cost data, or controls optimization to get a full picture of their potential, including: Large Air to Water Heat Pump for VAV Reheat and for fan coil unit heating, Aerosol envelope sealing, Blinds and Shades, Cool(er) Roof, and Thermal mass (concrete or phase change materials).

Many other efficiency upgrades were originally considered but rejected due to insufficient cost data, lack of required building and site-specific detail, energy plus not currently capable of modeling with sufficient accuracy, and others.

Meeting ZNE-TDV in ways that are TDV cost-effective does not imply energy-bill cost effectiveness, nor cost-effective reduction in greenhouse gas emissions. The additional construction cost per ton of marginal greenhouse gases carbon dioxide equivalent saved over 30 years.

Lessons for TDV Metric Development and Building Codes

Title 24 building codes have successfully included many of the societally TDV cost-effective efficiency measures but there are opportunities to tighten standards with societal benefit particularly with more climate zone specific codes and building type specific codes.

In the future, as more PV systems are connected to the grid, the TDV value of building attached PV systems is expected to decrease and this decrease may be faster than the decrease in cost of the PV systems. Many of the efficiency measures save energy at peak TDV times and may have an increase in TDV factor value. So future TDV factor values may bring more efficiency measures into TDV cost-effectiveness.

Opportunities to Make Stricter Codes

Building codes should require high efficacy LED lighting systems with lumens per watt of ~130 for troffer fixtures and ~145 for high bay fixtures because they are cost effective societally (TDV), for the builder (construction cost), and for the owner or occupant (utility bill).

This study identified areas where building codes could require higher efficiency levels that are societally cost-effective (TDV) in all California climate zones: Large-building variable air volume supply duct sealing, and Heat pump water heaters.

This study identified areas where building codes could require higher efficiency levels for specific building end use or construction types in specific climate zones that are societally cost-effective (TDV): Wall insulation for heavy mass walls in mild climates, evaporative cooling in very dry climate zones like 15 and likely others.

TDV Favors NG

The median TDV factor for electricity is larger than natural gas at corresponding time steps. For example, in climate zone 12 the median electricity TDV factor is 2.51 times the median natural gas TDV factor in the same units (kBtu/kWh) at corresponding time steps. This means that on a TDV basis natural gas combustion space heating and water heating is favored over electric options when the construction costs are similar.

Space Conditioning Heat Pumps

The TDV preference for natural gas makes upgrading roof top packaged equipment from natural gas furnaces to heat pump or natural gas boilers to heat pumps less cost-effective and disincentivizes these upgrades. Heat pump space condition options can still be cost-effective in climates where the peak cooling and heating loads are similar so that the equipment capacity does not need to increase and with sufficient heating degree days for the heat pump to save significant energy.

Water Heaters

This TDV preference for natural gas leads to natural gas hot water heaters being selected in multiple building types even though it increases greenhouse gas emissions. Heat pumps significantly increase heating efficiency above natural gas combustion and electric resistance but whether this increase is sufficient to overcome the TDV preference for natural gas depends significantly on heat pump costs, as well as selection of heat pump equipment efficiency curves dependent on outdoor conditions, supply temperatures, and on heat pump sizing.

Potential future work could investigate heat pump space heating and domestic water heating in greater detail than was possible in this broad study.

TDV Is Not Aligned With Marginal Greenhouse Gas Intensity

The greenhouse gas analysis conclusions subsection shows how TDV cost-effective packages of efficiency with PV or with battery systems have relatively high cost per tonne of CO2e saved. This is likely because the hourly TDV factors are incompletely aligned with the hourly marginal greenhouse gas intensity for each climate zone.

TDV Is Poorly Aligned With Utility Tariff Structures

The utility bills analysis conclusions subsection below shows how TDV cost-effective packages of efficiency with battery systems often increase utility bills as well as increase construction costs. This is likely because the utility tariff structures are poorly aligned with the hourly TDV factors for each climate zone.

Building Type Specific Results

Heavy Mass Walls

The Retail Standalone building type uses heavy mass walls for tilt up concrete construction as recommended for typical California construction practice (Skanska, 2019). Title 24 building codes allow relatively low baseline levels of wall insulation for heavy mass walls in CZ 2-10, so upgrading exterior wall insulation levels is TDV cost-effective. In cooling dominated climates heavy mass walls absorb heat throughout the day leading to higher cooling energy consumption in the late afternoon and evening hours which have now become peak times of grid stress and peak TDV factor values. For building types with schedules that have active cooling in the late afternoon and evening and in climate zones where outdoor temperatures remain high in the late afternoon and evening, additional wall insulation is cost-effective. If buildings have schedules that turn off cooling systems after 5 pm and or they are in climate zones where a large drop in outside air temperature allows economizer “free cooling” then the value of additional insulation will be lower. A significant factor in wall insulation cost-effectiveness is the reduced size of cooling systems to meet design day requirements. The cost reduction from reducing cooling system size can offset a portion of the added wall insulation costs. For Retail Standalone buildings in climate zones 2, 5, 7, and 10 the reduction in cooling system sizing and cost from additional wall insulation level 1 more than pays for the additional insulation so that the total construction cost is reduced. This suggests that stricter building codes could reduce construction costs and societal costs these climate zones. Also, in climate zones 8 and 9 the HVAC size and cost reductions almost completely pay for the additional wall insulation level 1. This analysis is sensitive to the size steps in insulation upgrades and to the building schedules in ways that interact with the climate zone, so even more detailed analysis may allow for even more granular optimum selection of the amount of additional insulation.

GHG Emissions Reductions Costs

The $/tonne CO_2e emissions reduction for battery systems is lower (better) than for PV. Batteries discharge at high TDV factor hours that align relatively well with high greenhouse gas intensity hours. In contrast PV systems export energy when the grid long run marginal greenhouse gas intensity is already very low.

The efficiency upgrades selected in the optimum packages typically have a lower cost per tonne CO_2e greenhouse gas emissions saved than either PV or batteries. Efficiency upgrades reduce the cost per tonne CO_2e greenhouse gas emissions saved compared to reaching or approaching ZNE-TDV with battery or PV alone. The most cost-effective individual efficiency upgrades reduced construction costs and would provide greenhouse gas emissions savings at zero or negative cost (Table 39).

Table 39: Efficiency Upgrade Additional Construction Cost per Tonne Carbon Emissions Saved Over 30 Years

	Climate Zone and City				
Efficiency Upgrade	**CZ 1** **Arcata** Cool Humid	**CZ 3** **Oakland** Mild Humid	**CZ 12** **Sacramento** Hot Summer Mediterranean	**CZ 15** **Palm Springs** Hot Desert	**CZ 16** **Blue Canyon** Mountain
HDD (65F)	4829	2637	2495	783	5410
CDD (65F)	3	155	1213	4336	470
Heat Pump Water Heater*	A) $110 B) $52 C) $24	A) $108 B) $50 C) $22	A) $109 B) $51 C) $23	A) $107 B) $50 C) $21	A) $139 B) $76 C) $30
RTU Heat Pump Heating	B) $71	B) $120	B) $74	B) $658	B) $94
Water Loop Heat Pump	A) Negative C) $11	A) Negative C) $18	A) Negative C) $19	A) Negative C) $81	A) Negative C) $12
Additional Wall Insulation	A) $1,671 B) $230	A) $3,971 B) $49	A) $2,309 B) $332	A) $2,354 B) $349	A) $1,157 B) $185
High Efficacy LED	A) $22 B) $2559	A) Negative B) $565	A) $31 B) $413	A) Negative B) $233	A) Negative B) $577
Supply Duct Sealing*	A) $46	A) $49	A) $48	A) $53	A) $56

(A) Large Office (B) Retail Standalone (C) Highrise Multifamily, * Overestimate of cost per tonne CO_2e reductions because upgrade not credited with reduction in required HVAC system size

Source: University of California, Davis

Upgrading to a heat pump storage tank water heater from an electric resistance baseline is one of the most cost-effective ways to reduce CO_2e emissions. The heat pump water heaters significantly increase efficiency and reduce electric energy consumption including during peak marginal greenhouse gas intensity times. The primary driver of the differences between building types is the quantity of hot water used per water heater with larger hot water uses resulting in greater energy savings and therefore greater CO_2e savings for the same upgrade cost. The large office has relatively low hot water usage per water heater, the retail stand alone has moderate hot water usage, and the high-rise multifamily has high hot water use.

Because heat pump water heaters remove heat from the interior conditioned spaces in a building, they can reduce cooling energy use in hot climates and increase heating usage in cool climates. This can be seen in the trend of cost per tonne CO_2e savings higher in cool climates and lower in hot climates.

Upgrading the rooftop packaged units (RTUs) from gas furnace heating to heat pump heating results in relatively cost-effective CO_2e reduction in CZ 1, 3, 12, and 16. CZ 1, 3, and 16 have a large number of heating degree days and very small number of cooling degree days, so that the heat pump operating time and therefore energy savings and emissions reduction is large. In CZ 12 the RTU capacity for heating is very close to cooling so that the cost is relatively low and there are still a significant number of heating degree days leading to significant emissions savings. CZ 15 has 783 Heating Degree Days (HDD (65)) and 4,336 Cooling Degree Days (CDD [65]) and much more extreme hot temperatures than cold temperatures so upgrading the RTU to heat pump heating requires a much larger capacity RTU with increased cost and the heat pump does not operate in heating mode for enough hours to save much energy and CO_2e.

In large buildings that use hot water recirculation loops to provide heat, such as the large office VAV reheat system and the high-rise multifamily fan coil units, a large air to water heat pump can replace the typical conventional gas fueled boiler. The air to water heat pump has a slightly higher equipment cost than the conventional boiler or a condensing boiler. Depending on the detailed building design the cost savings from reducing or eliminating gas pipes can reduce the additional construction cost or even make the total construction cost less than baseline. This modest construction cost increase or below baseline construction cost paired with the large energy savings from the heat pump led to very low or negative cost per tonne CO_2e reduction. For example, in the high-rise multifamily building it is assumed that gas piping would still be needed for gas ranges and ovens in the residential units so that the boiler gas piping costs reduce the construction cost premium for the water loop heat pump upgrade. In the large office there were no other gas end uses so that replacing the boiler led to an all-electric building that did not need any gas pipes reducing cost more than the equipment cost premium for the heat pump so that the construction cost was less than baseline and the cost per tonne CO_2e reduction was negative.

Upgrading wall insulation for the heavy mass walls in the Retail Standalone building type has variable cost per tonne CO_2e saved across climate zones likely because the baseline wall insulation requirement is different in the different climate zones. In climate zone 3 the baseline heavy mass wall insulation requirement is quite low and additional insulation has a large energy savings resulting in low cost per tonne CO_2e saved. For heavy mass walls climate zones 1, 12, 15, and 16 all have higher baseline insulation requirements and the diminishing returns to adding more insulation result in higher cost per tonne CO_2e saved. For the metal framed walls of the large office building type, all climate zones have fairly high baseline insulation requirements and the diminishing returns to adding more insulation result in very high cost per tonne CO_2e saved.

High efficacy LED lighting upgrades significantly reduce lighting energy consumption and also reduce waste heat generated in the building. In hot climates this reduction in waste heat reduces cooling energy consumption so that there is a double benefit reducing the cost per CO_2e reduction sometimes even resulting in a reduction in construction cost and listed in the table with a negative cost per tonne CO_2e saved. In cold climates reducing waste heat increases heating gas consumption reducing the CO_2e saved and resulting in higher cost per tonne CO_2e saved. In the large office building upgrades to a combination of high efficacy LED lighting in zones with the most daylight and very high efficacy LED lighting in zones without daylight in climate zones 3, 15, and 16 reduced the size of the HVAC cooling systems so much that upgrade construction costs were lower than baseline and there is a negative cost per tonne CO_2e saved.

Utility Bill Analysis

TDV factor values for electrical energy in climate zone 12 have a peak hourly value 55 times the average hourly value for the year. Utility tariffs have peak costs with much smaller multiples of the off-peak costs and typically only two seasons so they cannot provide incentives economically-efficient for private investment in societally cost-effective building upgrades.

To measure utility bill cost-effectiveness of upgrades, the additional construction cost for upgrades was added to the change in the 30-year net present value of the utility bills at a 5 percent discount rate to calculate the builder or owner total cost net present value. For efficiency plus PV packages in all climate zones the utility bills are reduced enough to more than pay back the additional construction cost of upgrades so that there was a net savings to the builder or owner. For efficiency plus battery packages the utility bills were reduced for some building types in some climate zones but in other climate zones the utility bills increased. Battery utility bills can be sensitive to charging power that increases the demand kW from the baseline scenarios making the upgrade ineligible for the original tariff. For example, the battery utility bill savings net present value more than pays back the cost of the efficiency plus battery upgrades for the multitenant light commercial building type in some climate zones but not in others. However, the efficiency plus battery upgrades increases the utility bills for the other building types in several climate zones. These complex trends are likely the result of different tariff structures and eligibility rules across different IOUs with changes from one tariff to another between baseline and upgrade cases having a significant impact. Table 40 provides an overview of the battery system impacts on the utility bill.

Table 40: Battery System Utility Bill Impact

	Climate Zones where Efficiency plus Battery Systems:		
Building Type	**Reduce utility bills enough to reach net present value savings**	**Reduce utility bills but net present value cost increase**	**Increase utility bills**
Warehouse		6, 8, 10, 12, 14-15	1-5, 7, 9, 11, 13, 16
Large Office	7	9, 13-15	1-6, 8, 10-12, 16
Retail Standalone		6, 7, 8, 9	10, 14-16
Multitenant Light Commercial	1-5, 7, 11-13, 16	6, 8, 9, 10, 14, 15	

Source: University of California, Davis

Very large battery systems are required to reach ZNE-TDV in large buildings. This study did not investigate the industrial utility tariffs and so very large battery systems were allowed to use commercial utility tariffs even if the increased demand kW power would make them ineligible. For this reason, the utility bills impacts for battery systems are expected to be underestimates.

Battery systems can increase utility bills depending on how charging timing and power align with utility tariff eligibility rules, fixed charges (meter charges), and demand charges. This suggests that current tariffs may significantly undercompensate battery systems for discharging when there is high value to the grid.

The TDV savings of batteries are sensitive to discharging timing and discharge power.

Combining PV and battery systems can achieve ZNE-TDV for all building types in all climate zones and has the potential to achieve a zero impact on NPV utility bill using the assumptions discussed previously.

Recent Construction Cost Increases

Recent increases in materials, equipment, and construction labor can influence the selection of upgrades that are cost-effective. For most efficiency measures cost increases of 20 percent or less will not change their selection in the cost optimum packages. Combination of energy efficiency upgrades plus PV systems and or battery systems can reach ZNE-TDV cost-effectively in all building types across all California climate zones, so a blanket increase in costs for all PV, battery, and efficiency measures would not change the optimum package measure selection since the efficiency upgrades are competing against PV and or battery systems. Construction cost increases would reduce the overall TDV $/$ cost-effectiveness but costs would need to increase by more than 34 percent across the board to make batteries or any selected efficiency upgrades not TDV cost-effective in climate zone 10 where batteries have the lowest TDV$/$.

Cost changes for PV, batteries, or any particular efficiency upgrade relative to costs for the rest could change the efficiency measure selection. The least cost-effective efficiency upgrades would be eliminated first if their relative costs increased or all the other costs decreased.

Limitations and Future Work

In the scope of this study numerous opportunities were identified to go deeper and broader to further improve the and expand the results.

This study did not consider:

- Equipment lifetimes and replacement costs beyond those for PV and Batteries
- Changes in maintenance costs from baseline to upgrades
- Future cost changes for energy efficiency upgrades
- Battery self-discharge, inverter efficiency curves, battery lifetime capacity degradation, additional interconnection costs for very large batteries
- PV detailed energy production simulation with panel temperature effects, dirt accumulation, and lifetime degradation

Technologies and strategies that were not considered for any building type due to limitations on availability of cost data or energy performance data or due requirements for much more detailed building systems designs:

- Advanced HVAC controls beyond typical practice including pre-cooling, load shifting, VAV terminal unit minimum flow setpoints, and other optimization strategies
- Load shifting strategies that reduce energy consumption during high TDV times
- Demand Controlled Ventilation
- Cost-benefit analysis of
    - Single speed vs variable speed motors for (water pumps, FCU)
    - Individual electric motor efficiency upgrades outside of whole equipment unit efficiency upgrades
- Natural ventilation
- Duct layout and oversized ducts
- Water pipe layout and pipe sizing
- Central water heating equipment, pipe layout, pipe insulation, pipe sizing, and recirculation controls
- Low voltage transformer efficiency upgrades
- Solar panel single axis tracking systems

Some interacting costs were not considered due to lack of available cost data or design details:

- Electrical service size and mechanical or electrical room size and space
- Natural gas distribution pipe costs from the nearest transmission branch to the site
- Rebates, tax credits, and other economic incentives
- Revenue streams or reduced utility costs for demand response programs or load flexibility
- HVAC system size and cost reductions from the following efficiency upgrades were not considered due to various limitations in EnergyPlus functionality
    - Indirect Evaporative Cooling
    - Evaporative Condenser Air Pre-Cooling
    - Evaporative Condenser Air Pre-Cooling and Ventilation Air Pre-Cooling

Future work could extend and deepen consideration of:

- Windows – More detailed selection of options tailored to each CZ and building type and options for aesthetically identical but different performing windows for different orientations
- Water consumption and ways to compare the value of water with energy and emissions benefits
- Possible building architectural changes
- For large buildings the following improvements could be undertaken in future work. Investigate tariff structures, tariff eligibility, and construction cost for electrical service at power levels higher than the commercial tariffs allow

VAV reheat hot water systems have very low efficiency during very low reheat demand times. Improving EnergyPlus modelling of these systems at very low load with large losses in the boiler(s), hot water distribution pipes, and issues like valve leak-by would give a more nuanced picture of the benefits of upgrades like condensing boilers or heat pumps. In addition, a small heat recovery chiller or heat pump could further enhance efficiency by cooling the chilled water loop and moving thermal energy to the hot water loop to satisfy the low reheat load times while avoiding activating large boilers or large heat pumps.

Large commercial buildings typically bring in a larger outside air flow rate than required for minimum ventilation to maintain a positive pressure inside the building. The amount of air flow required depends significantly on building envelope and exhaust shaft leakage. Because these leakage rates can vary significantly from building to building most simulations, including those developed in this study, assume outside air flow rates required for minimum ventilation. This significantly underestimates the benefits of envelope sealing and somewhat underestimates the benefits of air cooling and heating efficiency upgrades. Future work could improve models used in this study as well as those used for code compliance by measuring a larger sample of large commercial buildings to predict the range of expected outside air flow, envelope leakage, and exhaust shaft leakage.

Technology/Knowledge Transfer

The researchers prepared a Final Project Fact Sheet, Technology/Knowledge Transfer Plan, and Technology/Knowledge Transfer Report. The results of the simulations and the cost-benefit analysis will be made publicly available on the CEC website. Project findings will be disseminated via CEC report publication, technical papers and presentations to industry and government representatives including policy makers, regulators, building code developers, building designers, building developers, construction professionals, manufacturers and trade groups.

Benefits to Ratepayers

California's push for ZNE in new buildings will require building designers and builders to seek high efficiency energy system packages more aggressively for their buildings. To advance technologies that will facilitate ZNE in new buildings, builders, utilities, and policymakers will need solutions that are applicable to a variety of building types. This project provides optimized recommendations for TDV cost-effective energy savings/generation solutions for a wide variety of California's building portfolio for all 16 climate zones.

If TDV captures the true cost structure seen by utilities, and therefore ratepayers, the process of determining the maximum cost-effective level of net electricity reduction using the TDV metric should produce the lowest long-term total cost on a statewide level. Furthermore, using the TDV metric will place a higher value on technologies that reduce peak demand, which will increase grid reliability and safety. Detailed modeling of building energy modeling packages will allow for accurate determination of cooling and heating loads, enabling right sizing of equipment. This will further reduce peak demand and reduce equipment cycling, potentially extending equipment life for building owners. Lastly, several of the energy efficiency measures to be modeled including daylighting, passive solar orientation, and natural ventilation increase occupants' connection with outdoors, providing health benefits that are not captured in energy efficiency analyses.

The impacts of this project were estimated quantitatively using various sources and are summarized in Table 41. The CEC provided References for Calculating Energy End-Use, Electricity Demand and GHG Emissions was used to estimate the annual addition of floor area for different building types, and to calculate average energy use intensity for each building type (California Energy commission - EPIC Grant Program , 2015). For estimating the multifamily EUI, the number of existing multifamily units in California from the US Census was combined with multifamily electricity consumption in Attachment 12, assuming an average apartment size of 1000 ft^2. In addition, the ARUP report (Arup North America Ltd., 2012) was used to estimate breakdowns in construction rates between subsets of a given building type (for example 75 percent low-rise versus 25 percent high-rise multifamily). Also, in the multifamily market, according to the First Tuesday Journal (First Tuesday Journal, 2018), annual multifamily housing unit starts are projected to exceed single family housing starts in California at least through 2020, rising from 45,000 in 2015 to 75,000 units in 2020. Estimates are based upon 50,000 units per year, at an average size of 1000 ft^2.

- The other key assumptions required to estimate impacts were: a) the reduction in EUI in baseline new construction relative to the average data in References for Calculating Energy End-Use, Electricity Demand and GHG Emissions (assumed to be 20 percent across the board), and b) the assumed level of cost-effective energy efficiency that will be achieved from this project, which varies considerably between building types.

Table 41: Estimated Study Impacts

Building Type	Estimated Annual Construction Mft^2/year	Existing EUI kWh/ft^2/year	Estimated New-Const. EUI Reduction W/O Project	Estimated New-Const. EUI Reduction W/Project	Estimated Annual Savings (GWh/year)	Estimated Annual Savings (metric tons CO_2/year)
High-rise multifamily residential	12.5	3.68	20%	50%	13.8	4,568
Large Office	28.0	8.3	20%	50%	69.8	23,096

Stand-alone Retail	31.6	4.3	20%	80%	82.1	27,184
Multi-tenant light commercial (retail, office, food service)	24.8	4.7	20%	60%	46.6	15,433
Warehouse	24.5	3.4	20%	80%	50.5	16,707
Quick service restaurant	3.42	20.0	20%	40%	13.7	4,528
Full-service restaurant	2.28	12.5	20%	40%	5.7	1,887
TOTAL	**127**				**282**	**93,403**

Source: University of California, Davis

To interpret the table results correctly, the team assumed a 100 percent market penetration (as might occur if the cost-effective levels described are codified), and noted that the annual savings quoted are for each year of construction, such that they would continue to accumulate with time (for example 282 GWh the first year, 564 the second, 846 the third, and so on). Also, it should be noted that this analysis does not separately address gas savings or any potential fuel switching.

From a project cost benefit perspective, at a cost of $1 million, the cost of this project is small relative to potential benefits (one year of the technical potential savings is $45 million if electricity is valued at an average of $0.16 per kwh). That said, there will be considerably more costs incurred to implement the results of this project (such as demonstrations, code changes, building designer outreach and education.).

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APPENDICIES

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