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Multi-technology building system retrofits for utility incentive programs: Savings, costs and baseline considerations

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ABSTRACT

Utility incentive programs are an important channel to support the deployment of energy efficiency in buildings. To date, these programs have largely been limited to single-component strategies. However, many utilities are now motivated to identify and develop multi-component system retrofits to achieve deeper energy savings, which are essential to achieving broader energy and greenhouse gas reduction goals in the buildings sector. In this paper we present the energy savings, demand reductions, and cost-effectiveness of 16 systems retrofit packages in six utility regions in the United States. These results are being used by these utilities to inform and develop incentive programs for systems retrofits. Our analysis shows that packages with proven lighting and HVAC measures can provide 5–22% whole building annual energy savings, and 13–22% annual energy costs savings, using utility incentive program baselines (code and existing building). The packages are reasonably cost effective for replace-on-burnout but generally not for a retrofit scenario prior to end of equipment life. Demand response can increase both the energy savings and energy cost savings, further improving the cost effectiveness of these packages. We analyzed the impact of using existing building vs. code baselines for calculating savings, showing that the choice of baseline in developing utility incentive programs has a substantial impact on the attributable energy savings to a program, with significant implications for the overall viability of a program (generally savings against existing building condition are higher and improve project and program cost-effectiveness).

1. Introduction

1.1. Motivation and background

Energy efficiency in buildings remains an important strategy to achieve local, state and federal energy related policy goals, such as the U.S. government's target of a net zero energy economy by 2050 [47]. Energy efficiency (EE) savings continue to be an important contributor to reducing greenhouse gas (GHG) emissions, and must grow significantly in order to achieve GHG reduction targets [29]. However, EE deployment in buildings overall lags the timeline for these goals, and strategies are needed to deepen energy savings cost effectively. U.S. utilities are an important channel to support the deployment of EE strategies through customer incentive programs. Designed to motivate customers and improve the cost effectiveness of EE upgrades, utility incentive programs are a large driver for EE upgrades in U.S. buildings, and contributed to $5.6 billion in energy cost savings in 2018 alone [15]. Utility programs represent a significant investment in efficiency, predicted to reach $9.5 billion annually by 2025 [7].

Utility customer incentive programs have historically been focused on single component strategies, but multi-technology systems retrofits can provide substantially higher savings by working to leverage interactive effects or systems integration approaches [40,45]. In a previous effort, a set of utility partners worked to identify and deploy three system technology packages, achieving 49–82% greater energy savings compared to a standard component-based retrofit baseline [41]. Packaging multiple energy efficiency measures together strategically deepens energy savings by reducing overall internal and solar gains, reducing required HVAC system capacities and energy use. An integrated multi-measure efficiency retrofit can improve whole building energy savings by as much as 50% compared to just replacing single pieces of equipment [40]. However, one study indicated that only 9% of the projects in reviewed custom incentive programs (programs that allow for multiple measures but do not require integrated measure approaches) targeted system retrofits where the involved measures supported each other for deeper savings whether through

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interactive effects, or by collectively deepening the savings of an end use system [39]. It was more commonly the case that if a custom program did involve multiple technologies, they were disparate and not connected at the system level (e.g. separate lighting and domestic hot water measures), thus not creating the deeper energy savings found in integrated solutions. Utility custom incentive programs may offer an administrative approach for customers to implement multiple measures and receive an incentive for them; however here the onus is on the customer to develop this package of measures, contrary to the streamlined approach that utilities offer for single measure incentives where they offer greater degrees of measure identification and specification. Some utilities [33,43] have shown motivation to identify and deploy systems-level retrofits for their customers but the authors were not able to identify any other utility programs that offered a package of integrated energy efficiency measures, specifically designed to deepen energy savings through integration.

1.2. Research questions and goals

Utilities are looking toward multi-measure packages as they see dwindling savings occur through their existing single measure programs due to developments such as the increased saturation of efficient LED lighting in buildings and the growing stringency of energy codes which increases minimum efficiencies of installed equipment. Because of the energy savings potential of systems retrofits, there is a desire to enable package sets of EE measures within current utility program frameworks, which currently lean heavily towards lighting and HVAC. Generally utilities have lacked the information needed to identify specific systems-based retrofit strategies that save significant energy, and further lack the cost information to support the business case for deployment.

The question this study seeks to address is: what are the energy and cost saving potentials of multi-technology building systems retrofits that are assembled from energy efficiency measures (EEMs) that are readily available for utility program development? These EEMs would include technologies and controls that are accessible and deployable from current utility incentive program trade allies (e.g. lighting distributors, HVAC contractors), and have demonstrated previous acceptance as single measures in utility incentive programs, thus laying the groundwork for regulatory approvals of package incentives.

The goal of the research presented here is to produce useful reference information on the energy saving potential and cost effectiveness of different system packages in the context of utility programs, quantified in a way that is useful to utilities in their efforts to develop multi-technology systems retrofit programs. This goal was addressed through development of multi-technology system package concepts using existing and vetted EEMs, computer simulation of commercial building energy performance including with the system packages implemented, and analysis of the cost effectiveness of the packages. This study also explores how the energy and cost performance for these packages varies for different U.S. climate zones and utility rates, and depending on which baseline assumptions are made.

1.3. Further literature review

We find limited academic work on development of multi-technology EE packages, and specifically in the context of utility programs packages, energy simulation of packages, or the type of cost analysis as done here. More work in the packaged systems EE retrofits space has been done in the domain of public policy and efficiency advocacy organizations (for example non-governmental organizations and alliances). For example, opportunities for systems-level efficiency improvements are identified as dwarfing component-based approaches in [12]. The Alliance to Save Energy (ASE) also recommends that utilities promote EE rebate programs with integrated project design across end-use systems and that commercial buildings pursue "deep energy retrofits" conceptually consistent with systems-level multi-technology packages [1]. [48] defines "deep retrofits" in commercial buildings as integrated retrofit projects involving multiple building systems (windows, HVAC, envelope, and lighting given as examples) that cost effectively achieve at least 50% energy savings, and finds over two billion m^2 of eligible commercial building space in the US. The potential for higher energy savings from multi-technology packages has also been confirmed by the previously-cited Regnier and Sherman studies, but the area of research is still under-explored. [34] presents integrated system retrofit packages for commercial buildings for deeper energy savings, designed for deployment during routine real estate lifecycle events, including promising energy savings validation through lab tests for a multi-technology package with lighting, plug load, interior shading and HVAC controls measures. From analysis of a large dataset for high performance buildings, [31] finds that increased numbers of efficient technologies in a building does not always correlate to lower energy usage intensity, concluding that achieving high performance requires integrated design across technologies.

[22] and [28] have evaluated the cost of energy saved in EE program implementation from the utility perspective, finding costs that compare very favorably to the levelized cost of energy from generation and delivery, but this work is generalized across program portfolios regionally and nationally and does not address multi-technology systems concepts and costs as found herein. The gap between energy efficiency technology adoption given the proven value, in other words the apparent underinvestment in EE, is a salient problem that has been explored in [20] (gap overestimation, market forces, and behavioral economics explanations) and [19] (economic efficiency of EE products, energy operating costs, and unobserved cost inhibitions to EE adoption), though in relatively academic contexts and without attention to the role of multi-technology packaging of EEMs; nonetheless the relationship to this work is that successful development of cost-effective multi-technology packages could help close the identified gap. Finally, other work has attempted to define energy and cost savings for packages of retrofit measures, such as the International Energy Agency (IEA) Annex 56 on cost effective energy and carbon reductions in buildings [23], with cost effectiveness evaluated from the perspective of the customer. While this is of great interest to building owners, it is of limited value to utility program managers and implementers. The research presented herein attempts to illustrate an important pathway for utilities to adopt deeper energy saving programs, improving the viability and cost effectiveness for these strategies for customers.

1.4. Study approach

For this research effort, a consortium of five different utilities, representing six U.S. geographic regions (one of the utility partners represented two distinct regional service territories) partnered to identify measures and system packages of high relevance to their retrofit markets for analysis and evaluation to move forward into incentive programs. Each utility recommended that large commercial offices be the target sector for the study focus, and provided input into the energy efficiency measures considered for the packages. The potential to deepen energy savings in the six represented utility regions was explored through multi-measure incentive programs targeted for commercial buildings, while adhering to cost-effectiveness criteria for program acceptance. Consequently, EEMs were sourced from existing utility incentive programs, which already had received regulatory approvals, including passing utility-based cost effectiveness tests. To enable comparisons between the system packages across climate zones and utility rates, we standardize the analysis on a common prototype building model (dimensions, layout), with regional modifications to reflect the existing building stock in the region studied (e.g. wall insulation, window specifications). We describe the systems packages, the modeled energy and demand savings, and cost effectiveness by utility region. We conclude with implications for utility programs more broadly.

The combined utilities and regional service territories are referred to here as UTIL1, UTIL2, UTIL3, UTIL4, UTIL5, and UTIL6. Table 1 lists the geographic locations and climate zones of the partner utilities.

Table 1
Utilities included in the study.

Utility	Location
UTIL1	U.S. West Coast, ASHRAE Climate zone 3C
UTIL2	U.S. West Coast, ASHRAE Climate zone 3B
UTIL3	U.S. Central, ASHRAE Climate zone 5B
UTIL4	U.S. Midwest, ASHRAE Climate zone 6A
UTIL5	U.S. Midwest, ASHRAE Climate zone 5A
UTIL6	U.S. Northeast, ASHRAE Climate zone 4A

Utilities currently have considerable investment into the program design and administration of single measure programs, including infrastructure to market relevant technologies, and established deployment channels such as direct install programs and so called mid-stream incentive programs where the product vendor receives the incentive for each qualifying product sold. Given the large infrastructure investment in these programs, utilities are eager to continue to utilize these channels, and consequently many of the single measures considered for the packages stem from existing programs.

Various constraints to program design and delivery tend to favor simpler “widget” based program design, including administrative costs which run higher for highly-custom programs. A further constraint exists for many U.S. utility incentive programs where regulatory bodies have mandated that viable incentive programs must pass a cost effectiveness test in order to proceed. Many different cost effectiveness tests exist; however the most commonly applied criteria is the Total Resource Cost (TRC) test [16]. TRC essentially determines whether energy costs will go down in the territory as a result of implementing the efficiency measure (s). It compares the administration and customer costs to the avoided cost of generating the same amount of energy over the measure(s) lifetime [6].

Since all incentive programs in a utility territory will need to pass cost effectiveness tests, a methodology to develop the packages needs to consider this aspect. The methodology used here for developing these retrofit packages involved focusing on single measures that have already been deemed to meet the cost effectiveness criteria for each utility, which typically used the TRC methodology. Multi-measure incentive programs will also be required to meet this cost effectiveness test, so for the utilities studied, existing resources were reviewed to source candidate measures for the packages, such as their Technical Resource Manuals (TRMs), which indicate single measures already meeting the required cost effectiveness criteria and approved for single measure incentive programs. The measures found in the TRMs largely consist of HVAC, lighting and related controls measures, as well as select other measures relevant to process loads and domestic hot water, with little to no representation by envelope measures. It would have been advantageous from an energy saving standpoint to include envelope retrofit measures such as improved glazing or insulation in the proposed packages, thereby lowering heating and cooling loads and reducing energy consumption. However envelope retrofits are inherently costly to apply, and since they did not meet the cost effectiveness criteria of the existing programs, they could not be included in the packages while still delivering a set that would meet the required cost effectiveness tests.

1.4.1. Baseline selection

Energy savings estimates from retrofit technologies or packages are calculated against an assumed baseline condition, which includes assumptions about a building’s characteristics and conditions that lead to its annual energy usage (construction and materials details, operating schedules, mechanical equipment type, vintages, and efficiencies, etc.). The selection of a baseline in utility program design is a fundamental consideration in calculating savings, setting incentives, and program evaluation. Decisions on program baselines are typically set through a rule-making process involving utility program administrators, regulators and other stakeholders. Conceptually, this is relatively straightforward: the baseline is essentially the condition that would have existed absent the intervention. In practice, this is more complex because the counterfactual is not easily defined: it is highly context sensitive and requires defining or making assumptions about owner decision-making and building practices for existing building conditions. In addition, utility programs in some cases are held to regulatory requirements that mandate energy code baselines - a set of conditions that does not exist in most existing buildings. Consequently, defining a baseline is not a straightforward analytical process for existing buildings and requires stakeholder judgement and negotiation of competing interests across program regulators, implementers, customers and advocacy groups. While it was not the intent of this effort to conduct a comprehensive review of baseline selection practice nation-wide, we sought to identify the key issues through a selective literature review as well as discussions with key experts. We present the following highlights as context for the study presented in this paper:

- For new construction, the baseline is almost always defined as the prevailing building energy code. This is fairly non-controversial and we found no exception to this.
- For existing buildings, there are broadly two scenarios: 1) equipment being replaced before the end of useful life (EUL) while still being fully functional. This scenario is commonly referred to as ‘early replacement’ (ER) or ‘accelerated replacement’. 2) Equipment being replaced at failure or beyond EUL. This scenario is commonly referred to as ‘replace on failure’ (ROF) or ‘replace on burnout’ (ROB).
- Some programs apply an existing building baseline for ER and code baseline for ROF on the premise that the new equipment would or should have to meet current code. However, there are nuances even with this general approach. For example, the baseline framework developed for Massachusetts allows an existing building baseline for new ‘add on’ equipment such as a variable speed pump or energy management and information system [11]. Furthermore, deciding whether something is ER or ROB can be difficult in some cases and requires a preponderance of evidence to prove. California passed legislation mandating that the California Public Utilities Commission (CPUC) begin counting energy efficiency savings based on existing conditions [35].
- There is no widely accepted norm for defining an existing building baseline. Most programs define a common existing baseline to be applied to all buildings regardless of the actual existing conditions in a given building[1]. This baseline is usually deter-

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[1] In some unique cases, programs may allow an exception whereby the existing conditions of the specific building being retrofitted is used as the baseline.

mined based on 'industry standard practice' (ISP). ISP itself may be below, at, or above code depending on the equipment or measure.

- Computing savings over the lifetime of a measure may require the consideration of 'dual baselines,' wherein the baseline changes over the course of the measure lifetime. This is especially the case when future code changes can be anticipated with high certainty.
- For program evaluation purposes, there is an important distinction between what would have happened without the *measure* vs. what would have happened without the *program*, i.e., can the measure implementation and the associated savings be attributed to the program? In California, for example, utility programs can claim some (but not all) of the 'below-code' savings of an existing building measure, on the premise that utility programs help to improve code compliance, which remains a significant issue [36;18]. This is primarily an accounting issue on how to allocate savings between incentive programs and codes programs (i.e. programs that accelerate adoption of higher-efficiency building energy code), and not a technical issue on how to calculate savings for a measure. However, it is important in that it affects how much credit utilities can claim for energy savings and therefore whether they are able to offer viable incentives.

Our review also sought quantitative estimates of the impacts of selecting different baselines for a utility program. However, we found hardly any data on this. While there are many studies showing the savings potential of different measures, such as the California potential and goals study [36], these generally do not document the impact of different baselines[2]. A study by EnerNOC of energy savings for a range of energy efficiency measures [14] compared the amount of savings attributable to bringing existing building performance up to energy code minimum performance (to-code savings) and the additional energy savings the measures achieved beyond code minimum performance (beyond-code savings). For electricity, to-code savings was 18% while beyond-code savings was 9%; and for gas savings it was 12% and 3% respectively. To-code savings were substantially larger than beyond-code savings. In the context of energy baselines for efficiency retrofits, this implies that for retrofits in existing buildings, counting only energy savings beyond code may eliminate much or even the majority of energy savings achieved in actuality. [36] shows that two-thirds of the total electric savings and about half the total gas savings is from codes and standards programs; clearly building energy codes and appliance efficiency standards have moved the goalposts forwards significantly in terms of the minimum energy performance expected of new buildings and what efficiency measures must accomplish to get beyond code baseline performance.

The literature review and stakeholder discussions clearly affirmed that baseline selection is a significant issue. Toward that end, our analysis included consideration of code and existing building baselines. The existing building baseline provides an estimate of savings that customers can expect to realize, while the code baseline provides an estimate of savings relative to a code baseline that a utility may be obligated to use to determine incentive payments.

2. Methodology for systems analysis

We first selected several individual EE measures and combined these measures into different packages. We then used EnergyPlus [13] to simulate the energy savings due to implementing the packages. In order to quantify the effects of selecting different baselines, we simulated annual energy performance for energy code-compliant baselines as well as existing building baselines. EnergyPlus was selected as it provided thermal assessments of integrated building designs and solutions, while being a free, open-source platform that enables hourly time step energy outputs, which are needed to assess energy costs with various utility rate structures including demand charges. Finally, we estimated the cost to implement the packages and computed the resulting cost savings.

2.1. Measures and packages

To select EE measures for this study, we started by using a variety of sources [17,21,25–27,30,32,37,44,47] as well as conversations with industry experts, focusing on measures that were in existing TRMs and could provide strong potential for passing required cost effectiveness tests. We created an initial list of 71 measures that appeared to have good savings potential but are under-utilized; see Appendix Table A1 for the initial list of measures. We then asked each utility to rank the measures based on savings potential, program priorities, likelihood of adoption, and potential interest from customers. Finally, we selected 15 individual measures that ranked highly for all of the utilities; see Appendix Table A2 for a list of the selected measures and more detailed descriptions.

Next, we combined individual measures into packages using several considerations: We combined measures that could all be implemented by a single trade in order to leverage the fixed costs of contracting and mobilization of that workforce on site. We combined measures that leveraged the capabilities of other measures, whether interactive or integrated (e.g., the use of occupancy sensors in light fixtures to inform demand controlled ventilation). We combined measures based on scope of construction. We also picked some combinations of measures that were more applicable to retrofits. We added demand response (DR) to some packages, depending on whether the utility has DR programs in the service area. Some measures were also included specifically focused on HVAC systems, as this is an underutilized area in utility incentive programs [9]. In total, we developed and analyzed 34 packages of measures. Of these packages, 16 were prioritized based on utility partner feedback. We present results for those 16 packages here. The 16 packages include combinations of seven of the individual EE measures: efficient LED lighting with integrated and networked occupancy and daylighting controls, demand controlled ventilation (DCV) using occupancy sensor data from the lighting controls, zone-level temperature reset during unoccupied periods (also occupancy-sensor based), variable air volume (VAV) terminal box minimum flow retuning (from 30% to 15%) primarily to reduce reheat energy consumption, use of ceiling fans with cooling setpoint setback to reduce cooling energy when conditions are appropriate, ASHRAE Guideline 36 economizer controls improvements [3], and use of chilled water return for pre-heating of outside air. Four of the 16 packages also include DR measures such as cooling setpoint setback by 2.2 degrees C during DR events as well as lighting power reduction of 20% during DR events.

Table 2 lists the 16 packages for which we present results. It includes one lighting-only package (L1), eight lighting-and-HVAC (LH) packages, three HVAC-only (H) packages, and four DR packages. For each utility and service area, we evaluated each package relative to the appropriate baseline (discussed in the following section). We then narrowed our selection of packages to those with the most energy savings potential and best cost effectiveness.

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[2] We obtained mixed feedback on whether the baseline selection affects measure adoption.

Table 2
Prioritized set of packages and measures per package.

Category	Package Code	Measures
Lighting only	L1	Lighting (all) * includes LED fixtures, occupancy and daylighting controls
Lighting and HVAC	LH1	Lighting (all) + Zone-level temperature reset based on occupancy ("occ reset")
	LH2	Lighting (all) + Zone-level DCV
	LH3	Lighting (all) + Zone-level occ reset + DCV
	LH4	Lighting (all) + VAV box retuning
	LH5	Lighting (all) + VAV box retuning + Guideline 36 economizer controls
	LH6	Lighting (all) + Ceiling fans with cooling setpoint setback (2.2 degC)
	LH7	Lighting (all) + Ceiling fans with cooling setpoint setback (2.2 degC) + VAV box retuning
	LH8	Lighting (all) + Ceiling fans with cooling setpoint setback (2.2 degC) + VAV box retuning + Guideline 36 economizer controls
HVAC only	H1	Ceiling fans with cooling setpoint setback + VAV box retuning
	H2	Ceiling fans with cooling setpoint setback + VAV box retuning + Guideline 36 economizer controls
	H3	Chilled water return for outside air preheat + VAV box retuning
Demand Response	DR1	Lighting (all), zone-level occ reset and DCV, DR: lighting power reduction (20%) and cooling setpoint setback (2.2 degC)
	DR2	Lighting (all), ceiling fans with cooling setpoint setback (2.2 degC), DR: lighting power reduction (20%) and cooling setpoint setback with ceiling fans (3.3 degC)
	DR3	Lighting (all), ceiling fans with cooling setpoint setback (2.2 degC), VAV box retuning, DR lighting power reduction (20%) and cooling setback with ceiling fans (3.3 degC)
	DR4	Lighting (all), zonal DCV, DR: lighting power reduction (20%) and cooling setpoint setback (2.2 degC)

2.2. Modeling approach and baselines

We used building energy modeling and simulation to estimate energy saving potentials for the packages. We simulated annual whole-building energy use under baseline conditions and with the packages implemented using EnergyPlus models of large office buildings. The EnergyPlus building energy modeling application is DOE's flagship whole-building energy simulation engine to model sophisticated building energy systems and advanced controls, which enables evaluation of energy savings potential from the EE measures as a package for our study. EnergyPlus is widely used for building energy simulation studies to support the development of building energy code compliance, federal, state, and utility incentives programs, as well as the energy efficient design of new buildings and energy retrofit of existing buildings, and has been rigorously and continuously validated by ANSI/ASHRAE Standard 140–2020 [4].

The large office building model is approximately 46,500 m^2 with 12 floors, an aspect ratio of 1.5 (length-to-width), and a window-to-wall ratio of 0.4. For code baselines, we used an adaptation of the relevant DOE prototype models [38] that includes more detailed and realistic thermal zones. For existing building baselines, we used a detailed zoning version of DOE reference models [10], again with more detailed and realistic thermal zones. The standard version of these models has only five zones per floor. The detailed zoning version has about 26 zones per floor, as shown in the Fig. 1 example. The more detailed zoning was important for our analysis because some of the measures involve HVAC zone level controls that need a realistic diversity in zone conditions and behavior to illustrate energy benefits.

For packages with DR, we modeled all hours of the year without DR, then modeled all hours of the year again except with the DR strategy implemented for selected peak demand dates and hours, then combined the results for a year that included DR performance only on selected days. DR event parameters include duration, date, time of day, number of events per year, and incentive level per kW shed.

In addition to simulating the packages of measures, we also simulated individual measures in order to understand their individual impacts and for diagnostic purposes. We do not present results from the individual measures in this paper, but detailed results are available as indicated in the data availability section.

Table 3 shows the baselines and climate zones used for each utility. For UTIL3 and UTIL4, which use an existing building baseline, we used the pre-1980 vintage model for consistency with their programs. For the other utilities, which use a code baseline, we used the post-1980 vintage model for building envelope components, with code baseline for HVAC and lighting system performance[3]. For the utilities using a code baseline, we also did an analysis with existing building baselines, in order to understand the implications.

The pre-1980 reference model lighting power densities were consistent with T12 fluorescent lamps. However, most older existing buildings will have lighting systems that have been retrofitted to T8 fluorescent at a minimum. Consequently, for the UTIL3 and 4 existing building baselines, the lighting system assumptions were updated to the level of ASHRAE 90.1 2010, consistent with 3-lamp T8 fluorescent fixtures at lighting power density of 10.6 W/m^2 (open office).

2.3. Retrofit package cost estimation

Finally, we estimated costs for each package using a variety of sources: a construction industry cost estimate database [42], prior experience with equipment installation for other projects, market intelligence from industry experts, and discussions with lighting and HVAC manufacturers and suppliers. Retrofit costs were based on the estimated total cost of equipment and labor whereas replace on burnout (ROB) or new construction costs were based only on the incremental cost of the measure option compared to a 'standard' option (e.g., for lighting, basic LED or fluorescent fixtures without integrated sensors and controls).

Generally, for package costs, installation totals for a project depend on the estimated number of units installed, built up from project floor area and density of units per area, and estimated cost per unit (materials and installation labor). Costs per measure per package are given in Table 4 below, in terms of total project cost for the modeled building, and normalized to floor area. Cost details per measure are as follows:

- For advanced lighting (LEDs with integrated and networked occupancy and daylighting controls), we assumed a lighting fixture density of just over 7.4 m^2 per fixture, and approximately 41,800 m^2 of applicable space, and material costs per fixture of around $245 (troffer-style fixture with integrated sensors and controls) and labor costs per fixture installation of around $120 (includes controls commissioning).

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[3] Note that the code baseline applies only for the systems being retrofitted. For example: a building in which the HVAC and lighting are being retrofitted will be required to meet the code baseline for those systems. The envelope will still reflect existing building conditions.

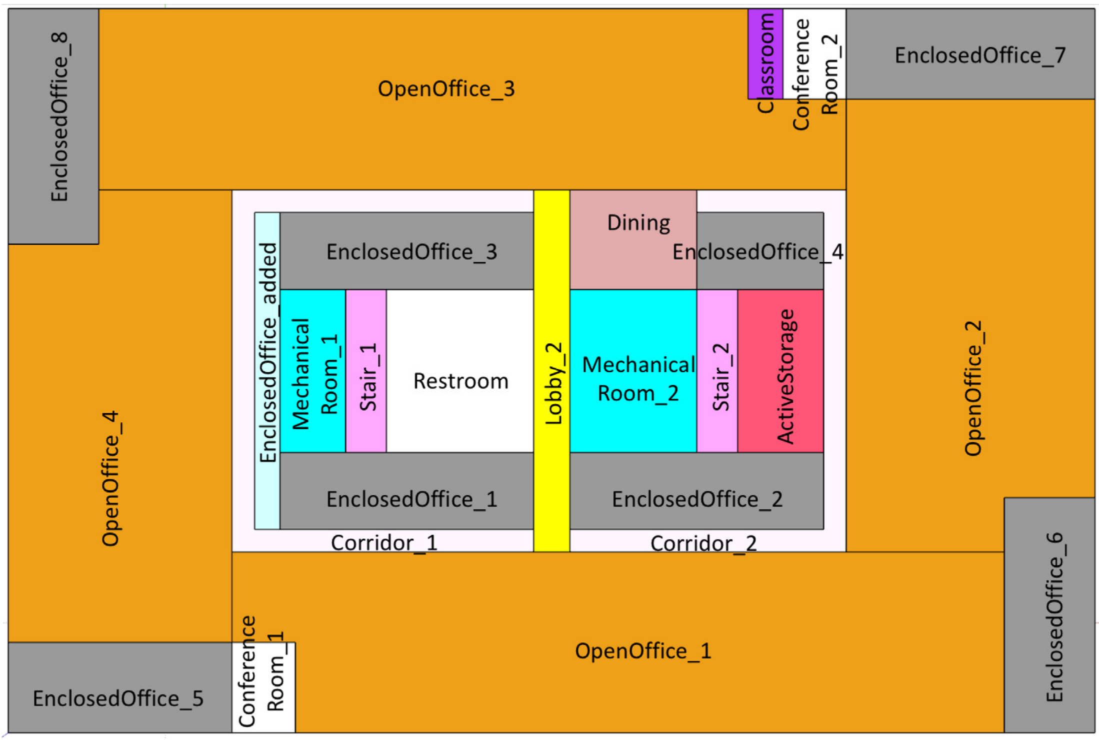

Fig. 1. Example floor plan showing thermal zones in the detailed zoning version of the commercial building prototype model used for the analysis.

- For zone-level HVAC setpoint reset based on occupancy control, the total served floor area was 38,370 m^2, at an implementation cost of $2.05/$m^2$ for labor only (zone setup and programming, but no equipment, since the lighting system occupancy sensors are used) [44,46].
- For zonal DCV using fixture-based occupancy, we assumed 90 total control zones per building, at 37,254 m^2 applicable floor area, and 415 m^2 per zone, and an implementation cost of $1,500 per zone (assuming $150/hour labor rate).
- For VAV retuning, quantities were based on one VAV box per 175 m^2 floor area, and 42,735 m^2 of total applicable area. We assumed costs of $50 per box for tuning and $1,200 to re-program the system.
- For ceiling fans and cooling setpoint setback, we assumed a total of 862 fans over 32,000 m^2 applicable area (around 37 m^2 per fan), and $400 material cost and $430 installation labor per fan and an additional $4,200 for the building for programming and commissioning labor.
- For Guideline 36 economizer controls, we used a simple $10,000 fee for programming and commissioning for the entire building.
- For chilled water return use for outside air (OA) preheating, we assumed six mechanical rooms building-wide where this would be implemented at the air handling unit (AHU), and equipment costs based on building floor area of $0.07/$m^2$, labor costs of $0.15/$m^2$, as well as $1,500 for each AHU for an additional coil and programming [17].
- Assumed costs to implement the DR programming for DR packages ranged from $10,000 to $12,000 per building, based on number of zones, assumed costs of $150/zone programming and building-wide DR commissioning fees.

2.4. Utility rates, energy costs, and simple payback approach

Modeled annual energy usage (electricity and natural gas) and monthly peak electric demand for baseline and retrofit scenarios were converted to dollars based on commercial customer utility rates for each partner utility. Rates included energy and demand charges for electricity, with time of use (TOU) tiers in most cases, and natural gas charges, as summarized in Table 5.

Table 3
Baselines for each utility.

Utility	Baseline
UTIL1	Code: California Title 24 2016
UTIL2	Code: California Title 24 2016
UTIL3	Existing Building: DOE pre-1980 reference model
UTIL4	Existing Building: DOE pre-1980 reference model
UTIL5	Code: ASHRAE 90.1 2013
UTIL6	Code: ASHRAE 90.1 2016

Package installation cost estimates along with annual energy cost savings based on the utility rates were used to calculate simple payback for the packages. Dividing package cost by annual cost savings results in the number of years needed for the package to pay back in savings the costs required to implement it.

The simple payback (SPB) approach provides a quick and easy comparative reference for the cost effectiveness of the retrofit packages (to the customer) and is a common and accepted metric for EE measure analysis. However, as the term implies it is a “simple” approach, with limited applicability for understanding full lifecycle cost effectiveness. It does not account for cost of capital, an investor’s discount rate, nor does it include the ongoing cost savings over the total effective useful life of a measure, and it does not consider lifecycle variables such as energy cost escalations and inflation. Net present value (NPV) and internal rate of return (IRR) calculations provide a more sophisticated cost effectiveness picture for efficiency measure financial analysis. However, such analyses require more inputs and may be less generalizable and were not in the scope of this research effort. Further, with utility program viability being a key consideration, simple payback was deemed an effective metric for comparison across the system packages at this stage, for the purpose of ranking and prioritizing the

Table 4
Package cost details.

Measure	Packages with Measure	Estimated Cost / Building*	Estimated Cost / Square Meter
Lighting and controls	L1, LH 1 – 8. DR 1–4.	$2,017,000	$48.25
Zone level occupancy-based temperature reset	LH 1 & 3. DR 1.	$78,500	$2.05
Demand controlled ventilation	LH 2 & 3. DR 1 & 4.	$135,000	$3.62
VAV box retuning	LH 4, 5, 7 & 8. H 1 – 3, DR 3.	$13,400	$0.31
Ceiling fans with temperature setback	LH 6 – 8. H 1 & 3. DR 2 & 3.	$723,000	$2.27
Economizer controls	LH 5 & 8. H 2.	$10,000	$0.22
Chilled water return OA preheat	H 3.	$19,350	$0.42

* Costs are given for UTIL2 and represent base costs for the analysis, which were scaled per utility based on regional differences in costs for labor and materials relative to UTIL2.

packages for further program development. Should a package move into development, deeper cost effectiveness tests would be applied, such as the TRC metric described earlier.

3. Results and discussion

As noted previously, we analyzed 34 packages. We present below the results for the 16 packages that were prioritized in discussion with the utilities. The prioritization was based on the savings, cost effectiveness, as well as utility program considerations such as applicability to their customer base.

We include here results and discussion of baseline energy use, energy savings, energy cost savings, peak demand savings, savings per end use, simple payback, and comparison of code vs. existing building baselines. For brevity, we present summaries and selected charts. Complete results for all utilities are available as explained in the data availability section.

3.1. Baseline energy use

Fig. 2 shows the baseline energy use breakout for each utility. The breakout varies considerably across the utilities. Lighting and plug loads are the dominant end uses for UTIL1 and UTIL2. Heating, plugs and lighting are the largest end uses for UTIL3, UTIL4, UTIL5, and UTIL6.

3.2. Energy use savings

Table 6 shows the range of site energy use savings percentages. There is a wide range of savings across the packages. As expected, the LH packages, which combine lighting and HVAC, show higher savings than the L and H packages. The maximum savings range from 12 to 22% across all six utilities. L package savings are higher in UTIL1 (10%) and UTIL2 (11%) because lighting is a higher portion of baseline site energy for those utilities. H packages savings are higher in UTIL3 (9–10%) and UTIL4 (14%) compared to other utilities, partially because they have existing building baselines. H packages savings are lowest in UTIL1 (5%) and UTIL2 (4%), likely due to the mild climate and a relatively smaller proportion of HVAC energy use generally. The relative differences between the packages are similar across all six utilities. As an example, Fig. 3 shows the package savings for UTIL6. Lighting (all) and VAV box retuning appear to be the key measures included in packages with high savings.

3.3. Energy cost savings

Table 7 shows the ranges of site energy cost savings percentages per utility. Cost savings percentages are higher than energy use savings percentages. The maximum savings range from 15 to 26% across all six utilities. Energy costs include fixed costs and demand charges. Demand savings percentages are considerably higher than the energy use savings percentages, as discussed later, which consequently has a greater influence on the overall energy cost savings. Cost savings show a narrower range across packages than the energy use savings. The relative trends across the packages are similar across all six utilities, and are consistent with the trends for energy use savings. As an example, Fig. 4 shows the energy cost savings for UTIL3. As with energy use savings, Lighting (all) and VAV box retuning appear to be the key measures for packages with high savings.

3.4. Peak demand savings

Table 8 shows the range of annual peak demand reduction and savings percentages for all the packages, including the DR packages. These are considerably higher than the energy use savings percentages for the L, LH, and H packages. The maximum savings range from 20 to 35% across the six utilities. The savings for the DR packages were in the same range, with maximum savings from 20 to 38% across five utilities that considered DR packages (UTIL5 did not). In all five utilities, DR3 had the highest savings (Lighting all, ceiling fans with cooling setback and VAV minimum retuning). Again the relative trends across the packages were similar for all the utilities. As an example, Fig. 5 shows the demand savings for the L, LH, and H packages for UTIL1, and Fig. 6 shows the same for the DR packages for UTIL1.[4]

3.5. Savings breakout by end use

Fig. 7a-c shows the savings in lighting, HVAC electricity and gas energy as a percentage of total site energy use for UTIL1, UTIL3 and UTIL6. Lighting energy savings are highest in all packages with lighting measures, and significantly outweigh HVAC electric energy savings, up to ten times for some packages. However, we note that HVAC electric savings are somewhat underestimated for packages with VAV retuning due to modeling limitations in EnergyPlus - the software does not include a fan system model that can replicate system pressure and flow dynamics and therefore cannot adjust fan energy for the lower minimum VAV box setting. The packages with VAV retuning have high gas energy savings, due to reduced need for reheat for VAV boxes in low flow conditions, despite the savings penalty due to lower lighting load. Other L and LH packages show a gas penalty due to the lower lighting load. The penalty is generally about a third of the lighting savings for UTIL3 and UTIL6 but much lower for UTIL1, due to the milder climate.

3.6. Cost effectiveness

Table 9 shows the simple payback (SPB) results for the packages for two implementation scenarios as described earlier: retrofit

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[4] Interestingly, the savings in LH4 (lighting and VAV retuning) is lower than the savings in L1 (lighting only). This appears counter-intuitive. However, further investigation indicates that the likely reason is that the VAV retuning measure reduces night cooling of the thermal mass, which results in the need for slightly more cooling during the day and an associated increase in peak peak demand relative to L1.

Table 5
Utility energy and demand charges used in payback analysis.

Utility	Energy Costs			Demand Costs				Gas Costs
	Min Energy Charge ($/kWh)	Max Energy Charge ($/kWh)	TOU Tiers	Seasonal / Monthly Demand Charge ($/kW)	Min TOU Demand Charge ($/kW)	Max TOU Demand Charge ($/kW)	TOU Tiers	Average Charge per Therm
UTIL1	$0.09	$0.15	5	$19.60	$0	$20.22	4	$0.77
UTIL2	$0.06	$0.33	5	$19.02	N/A	N/A	N/A	$0.66
UTIL3	$0.03	$0.04	2	$20.58	N/A	N/A	N/A	$1.31
UTIL4	$0.03	$0.07	2	N/A	$0	$15.54	3	$0.77
UTIL5	$0.068	$0.074	2	$7.48	N/A	N/A	N/A	$0.60
UTIL6	$0.12	$0.12	N/A	$25.41	N/A	N/A	N/A	$0.71

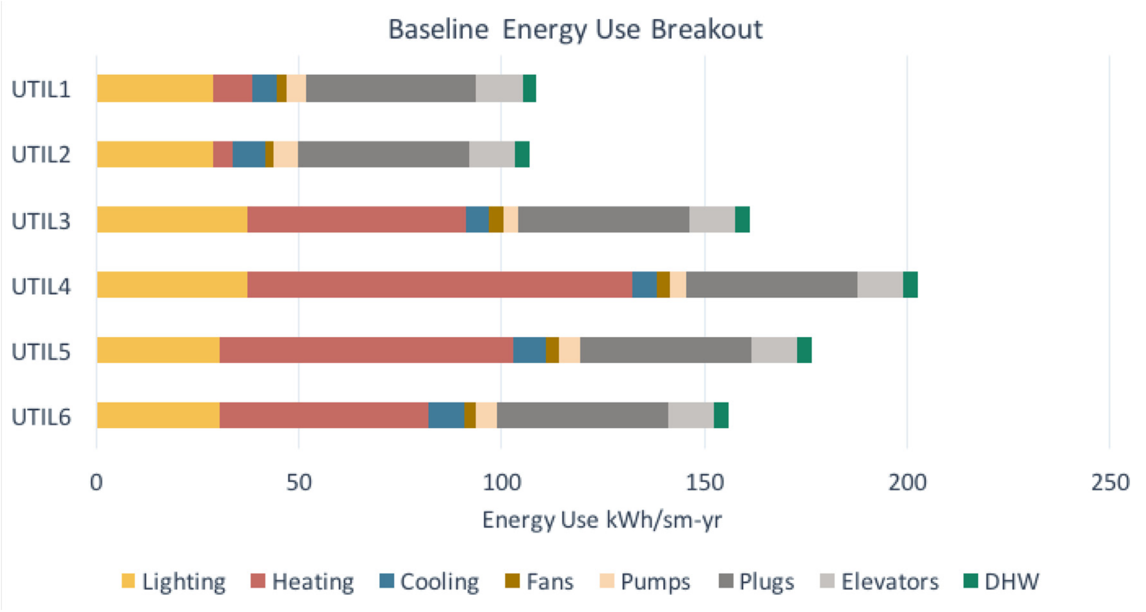

Fig. 2. Baseline energy use for each utility. Note that UTIL3 and UTIL4 are existing building baselines. All others are energy code baselines for retrofits.

Table 6
Energy use savings percentages for packages.

Utility	Site energy use savings range (%)		
	Lighting only package	**Lighting + HVAC packages**	**HVAC only packages**
UTIL1	10%	10% – 16%	5%
UTIL2	11%	11% – 16%	4%
UTIL3	8%	10% – 20%	9% – 10%
UTIL4	6%	6% – 22%	14%
UTIL5	5%	5% – 12%	7%
UTIL6	6%	6% – 14%	7%

(RET) and replace on burnout (ROB). In most packages, ROB has much lower SPB because it only includes the incremental cost over the baseline equipment replacement cost, whereas in the RET case the SPB accounts for the entire cost of the retrofit. Note that RET and ROB are identical for the H packages because they do not involve equipment replacement. As expected, payback is much lower for utilities with higher energy costs, such as UTIL1 and UTIL6, with less than five years for several L and LH packages for ROB. But even UTIL5, which has the lowest energy costs of all the six utilities, has SPB less than 10 years for ROB for several packages. LH4 and LH5 generally have the lowest SPB across all the utilities. Packages with ceiling fans have significantly higher SPB. This is driven by the low savings rather than the cost of ceiling fans. Although the SPB values varied across the utilities, the relative differences between packages were similar for each utility. Fig. 8a-b shows the SPB values for UTIL5 and UTIL6 as examples.

While ROB may have the advantage of a quicker financial return on the retrofit, it does present some additional challenges in execution. Practically, the building owner needs to carefully plan for the retrofit to occur in conjunction with the end of useful life of the given equipment, which can be hard to predict, and risky from the standpoint of assurance of continued operation until the point when the retrofit is ready to occur. Some of this risk can be mitigated by tracking equipment lifespan and depreciated value, and planning for the replacement in advance, coordinating with other related retrofit work. The retrofit will be disruptive to an occupied building whether it is timed to occur at the end of useful life of the equipment or not. However, by introducing the assessment of value of installed systems and equipment into the capital planning process, ROB retrofits can be planned for ahead of time.

3.7. Impact of code vs. existing building baselines

As previously described, the selection of a baseline is a fundamental consideration when structuring and designing an incentive program. Individual projects have to adhere to the baseline requirements when calculating their incentives, regardless of the actual baseline for a given project. UTIL1, UTIL2, UTIL5 and UTIL6 use an energy code baseline for retrofits while UTIL3 and UTIL4 use an existing building baseline. Utilities using code baselines are keen to understand the difference between code and existing building baselines, since this in effect represents the additional savings experienced by the building owners even though they do

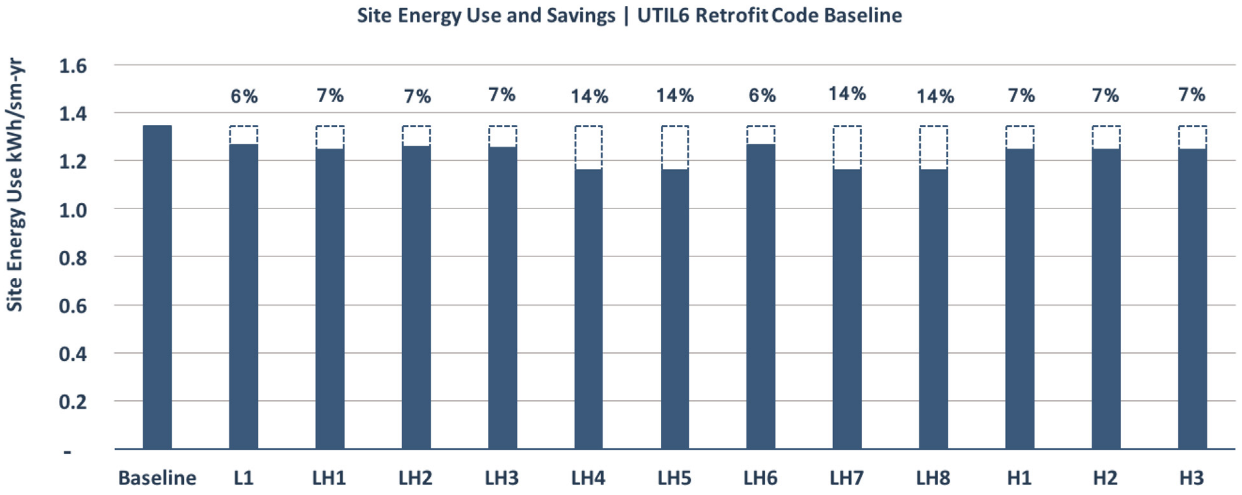

Fig. 3. Site energy use and savings for UTIL6.

Table 7
Energy cost savings percentages for packages.

Utility	Site energy cost savings range (%)		
	Lighting only package	Lighting + HVAC packages	HVAC only packages
UTIL1	16%	16% – 18%	1% – 3%
UTIL2	15%	15% – 16%	0% – 1%
UTIL3	14%	15% – 24%	7% – 8%
UTIL4	18%	19% – 26%	5% – 7%
UTIL5	12%	13% – 16%	3% – 4%
UTIL6	13%	13% – 16%	2% – 4%

not get incentives for the additional savings. Fig. 9a-b compare the savings based on code and existing building baselines for UTIL1 and UTIL6. For UTIL6, the existing building baseline yielded almost double the savings in many packages. For UTIL1, the existing building baseline yields about a quarter to a third more. UTIL5 results were similar to UTIL6 and UTIL2 results were similar to UTIL1. These packages may offer a significantly higher value proposition for owners than what the utility program itself suggests.

3.8. Indoor environmental quality

The viability of a set of technologies in achieving acceptance and satisfaction by the building's occupants and users is tied to occupant experience of indoor environmental quality (IEQ), including the space's thermal comfort metrics. The developed retrofit packages are intended for application in a range of existing buildings with unknown degrees of current IEQ, and as such it is not possible to quantify potential improvements in IEQ through this study. However the packages can be assessed for ability to comply with industry standards quantifying aspects of IEQ using the baseline model conditions for comparison. ASHRAE Standard 55 'Thermal Environmental Conditions for Human Occupancy' provides metrics and ranges for acceptable human comfort involving indoor dry bulb temperature, relative humidity, mean radiant temperature and air velocity [5]. The simulation models in EnergyPlus v9.1 include assessment of several thermal comfort metrics, including the amount of time the space is considered not comfortable based on ASHRAE 55.

For UTIL1 and 2, which are located in temperate climates, both the existing building baseline and all package simulation results indicate that thermal comfort was achieved during the year, with only minor variances outside of this range (e.g. weighted average

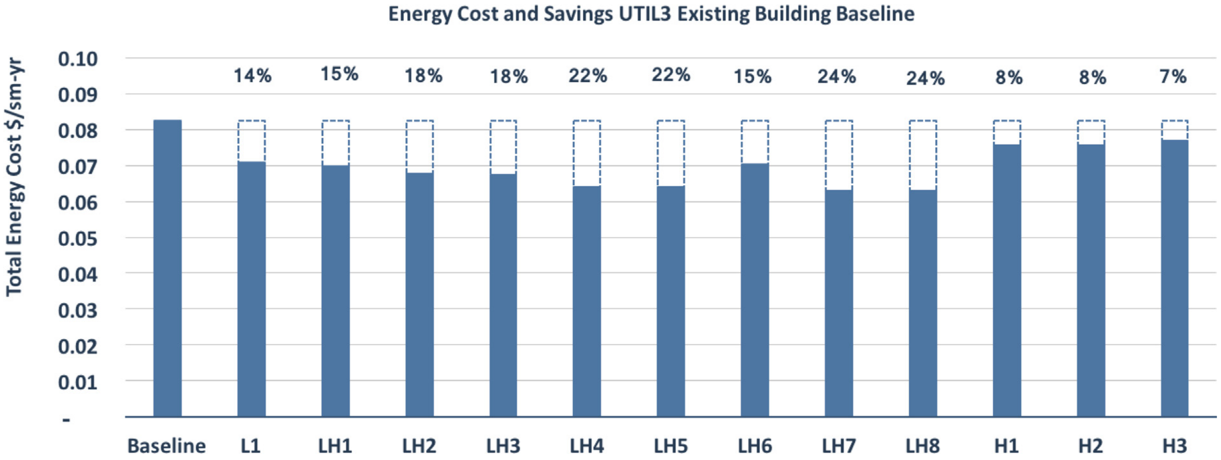

Fig. 4. Energy costs and savings for UTIL3.

Table 8
Peak demand savings percentages for packages.

Utility	Site demand cost savings range (%)			
	Lighting only package	Lighting + HVAC packages	HVAC only packages	DR packages
UTIL1	20%	18% – 24%	0% – 10%	27% – 30%
UTIL2	19%	19% – 20%	0% – 2%	25% – 26%
UTIL3	30%	28% – 35%	0% – 11%	31% – 38%
UTIL4	21%	21% – 30%	0% – 7%	26% – 34%
UTIL5	16%	16% – 26%	2% – 9%	n/a
UTIL6	20%	17% – 26%	0% – 9%	21% – 32%

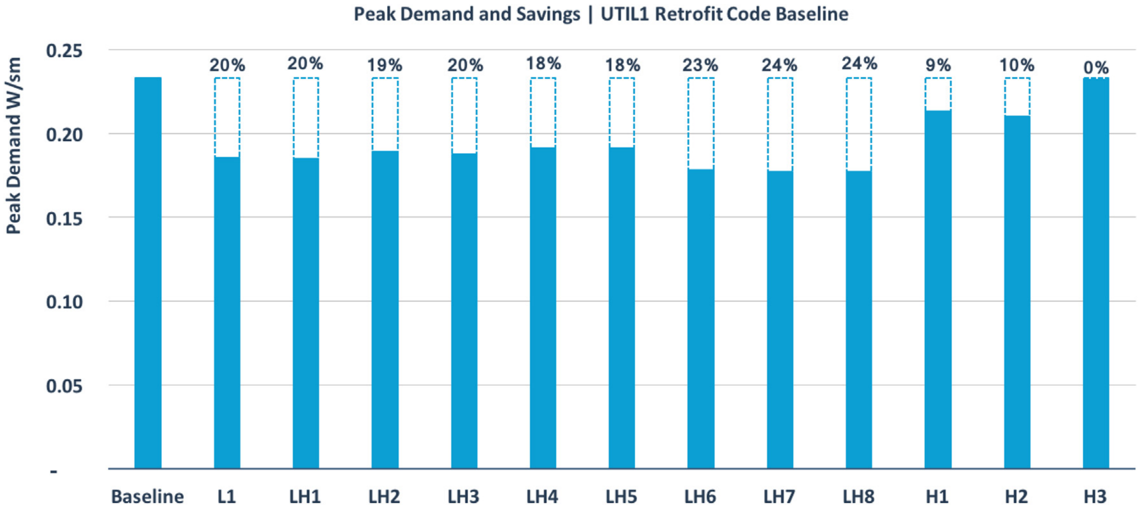

Fig. 5. Peak demand and savings for UTIL1.

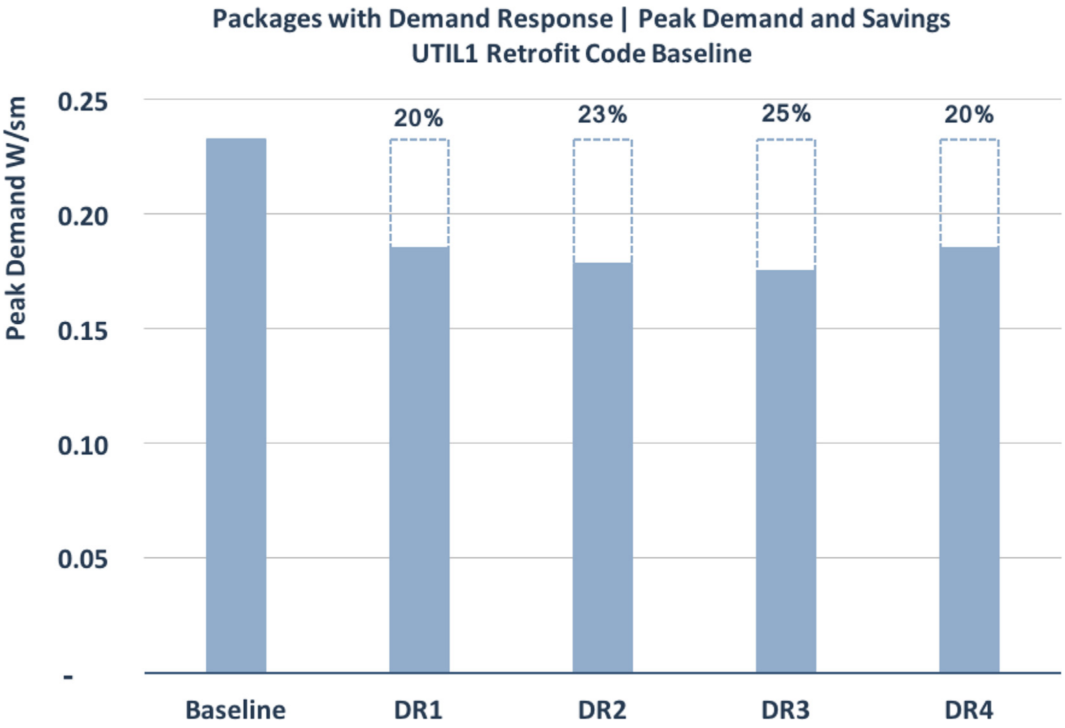

Fig. 6. Peak demand and savings for UTIL1 for DR packages.

Fig. 7. a-c. Savings end use breakout for UTIL6 (a), UTIL1 (b) and UTIL3(c).

thermal comfort results were out of comfort bounds for 1–5% of occupied hours for both the baseline and package cases). There was no significant difference in delivery of thermal comfort for any of the packages as compared to the baseline building's performance.

UTIL3, 4, 5 and 6 however are located in cool and cold-leaning climates with baseline energy models representative of buildings with poor envelope conditions. For example, UTIL5 and 6 large office models represent post-1980 vintages that meet ASHRAE 90.1 1989 standards for envelope compliance; UTIL5 has an RSI-value (K·m^2/W) of 1.59 for exterior walls and 3.17 for roof, and UTIL6 has RSI-1.23 exterior walls and RSI-2.82 roof. Building models for UTIL3 and 4 represent pre-1980, and envelopes properties are based on the ASHRAE 90A-1980 [2]. UTIL3 has RSI-1.06 exterior walls and RSI-2.29 roof, and UTIL4 has RSI-1.23 exterior walls and RSI-2.99 roof. All of these utilities have poor-performing

Table 9
Simple payback (SPB) for packages for retrofit and replace-on-burnout.

Utility	**Simple payback (years)**				
	Lighting only package		**Lighting + HVAC packages**		**HVAC only packages**
	RET	ROB	RET	ROB	RET, ROB
UTIL1	13	3	13–18	3–8	7–36
UTIL2	16	4	15–21	4–9	13–59
UTIL3	29	8	19–37	5–16	1–16
UTIL4	16	4	12–21	3–9	1–15
UTIL5	33	8	27–44	6–19	2–42
UTIL6	16	3	14–22	3–9	2–23

Fig. 8. a-b. Simple payback on retrofit and replace-on-burnout for UTIL6 (a) and UTIL5 (b).

single-pane glazing windows with U-value (W/m^2·K) of 0.17. Note that all baseline model conditions were selected for assessment by the utilities as being representative of the building stock they would target for the package improvements. The baseline energy models for UTIL3, 4, 5 and 6 all indicated that there would be significant time periods with indoor conditions outside of the comfort range prescribed by ASHRAE Standard 55 (17–23% of occupied hours). The poor-performing building envelopes are a substantial contributor to this result, with low mean radiant temperature in the winter months, lowering the operative temperature felt by the occupants and causing uncomfortable conditions. Overall, all of the studied packages had a similar thermal comfort performance to the baseline model, with no significant additional benefits or negative impacts (retrofit package models showed conditions outside the thermal comfort range 15–27% of occupied hours). It is expected that for overall thermal comfort acceptance and improvements in these cases, significant investments in improving building envelope would be required, which was outside the scope of this study.

In terms of visual comfort, EnergyPlus v9.1 does not include photometric simulation of electric light or daylight conditions. However, the lighting power densities in the energy model and

Fig. 9. a-b. Comparing savings from code and existing building baselines for UTIL6 (a) and UTIL1 (b).

the associated lighting technologies in the reference baseline and in the retrofit packages (T8 fluorescent troffers and LED troffers, respectively) are consistent with lighting output that would deliver minimum design task illuminance levels, such as per Illuminating Engineering Society (IES) recommended practice [24]. Daylight delivery and glare probability from the windowed facade is also outside of the scope of the simulations, but the package technologies have no impact on daylight delivery from the facade; e.g. no changes to window transmittance, blinds configuration, etc. Daylighting controls are a package measure that would affect electric light delivery in the daylit zone, but are presumed to be commissioned correctly, at a dimming setpoint that still maintains minimum task illuminance targets.

4. Conclusions

Collectively, the key findings from these results are:

- Packages that include lighting and VAV retuning offer the highest value in terms of savings and cost effectiveness. Additional measures offer fairly marginal benefits.
- The relative trends across the packages are fairly consistent across the six diverse utilities, suggesting that these trends may hold for other locations as well.
- Energy savings from lighting far outweigh the savings from HVAC.
- The packages offer significant demand reduction.
- The packages are reasonably cost effective for replace-on-burnout but generally not for a retrofit scenario.
- The use of an existing building baseline shows significantly higher savings than a code baseline.

We presented and discussed these results with the utilities. Some of the utilities decided to work on the development of an incentive program for two packages: 1) Lighting and VAV retuning; and 2) Lighting and DCV. Existing buildings will continue to be a significant portion of U.S. building sector energy use, and will require cost effective retrofit strategies that can offer deeper savings over traditional component based retrofits. Systems retrofits that combine multiple measures can offer deeper savings, but remain underutilized in utility programs. In collaboration with six utilities, we identified and analyzed 34 systems packages for energy savings, demand savings and cost effectiveness. Our analysis shows that packages with proven lighting and HVAC measures can provide 5–22% whole building annual energy savings, and 13–22% annual energy costs savings. The packages are reasonably cost effective for replace-on-burnout but generally not for a retrofit scenario. Packages that include lighting and VAV retuning offer the highest value in terms of savings and cost effectiveness. Additional measures offer fairly marginal benefits. Demand response can increase both the energy savings and energy cost savings, further improving the cost effectiveness of these packages. With the rise of intermittent renewable energy in utility supply, building technologies that are capable of providing demand response will increase in their value as event and price based demand reductions become increasingly important.

The choice of baseline in developing utility incentive programs has a substantial impact on the attributable energy savings to the program, and hence the viability of a program proceeding. Energy savings from a retrofit technology or package relative to an existing building's actual conditions will generally be much higher (particularly for older building vintages); these are also the "real" energy savings that the implementing building will experience over time, for example, in terms of dollar savings in utility bills. However, regulations and policies often require that utility programs only account for, or "claim," retrofit energy savings relative to a current building energy code baseline. In cases where energy code is a required baseline, there will be conditions where a technology or system package of measures will not be able to meet utility cost effectiveness tests for administration of the program (due to lower admitted energy benefits). Ultimately this is a detriment to the customer, as they would lack access to the incentives needed to help improve their cost effectiveness deployment of the energy saving technologies. Efforts are under way in some cases, such as the California Public Utilities Commissions' Energy Efficiency Baseline Analysis [8], to explore possible pathways for existing buildings to adopt more relevant baselines, such as by attributing existing building baselines for the remainder of the useful life of the measure, and including code baseline savings for the remainder of the life of the measure.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A – Energy Efficiency Measure Lists

Table A1
List of initial efficiency measures (EEMs) considered for retrofit packages.

Building System Type	EEM Name	End Use System Element
HVAC	Air-source heat pump (ASHP)	Equipment
HVAC	Variable capacity heat pumps (mini, multi-splits)	Equipment
HVAC	Cold climate ASHP	Equipment
HVAC	Variable refrigerant flow (VRF) conditioning system	Equipment
HVAC	ASHP with smart controls	Equipment
HVAC	Very high efficiency dedicated outdoor air systems (VHE DOAS)	Equipment
HVAC	Hybrid rooftop unit (RTU) with dual evaporative pre-cooling	Equipment
HVAC	Sub-wet bulb evaporative chiller (for hot/dry climates)	Equipment
HVAC	RTU optimization package - condenser evaporative air-pre-cooler	Equipment
HVAC	Programmable ceiling fans and smart thermostats	Equipment
HVAC	*Thermafuser* diffusers, occupancy and setback controls	Equipment
HVAC	RTU airflow tuning	Equipment
HVAC	Liquid cooling in data centers	Equipment
HVAC	Energy-smart pressure independent controlled chilled water valves	Equipment
HVAC	Space heat recovery from refrigeration	Equipment
HVAC	Backward curved fan impeller	Equipment
Lighting	LED task lights	Equipment
HVAC, Lighting	LEDs, luminaire specific occupancy and temperature sensing	Equipment
Lighting	LEDs, luminaire specific occupancy sensing	Equipment
Plug Load	Advanced power strips	Equipment
DHW	Commercial heat pump water heaters	Equipment
Envelope	High-performance window attachments (films, blinds, storm windows, secondary glazing systems, awnings)	Equipment
Envelope	West facing facade shading	Equipment
HVAC	Chilled water return use for outside air pre-heat	Controls
HVAC	Chilled water system embodied cooling (without chiller on)	Controls
HVAC	Cooling tower fan staging	Controls
HVAC	Condenser pump sequencing (optimize based on efficiency curves)	Controls
HVAC	Heat recovery coil controls	Controls
HVAC	Wet bulb temperature control	Controls
HVAC	Refine outdoor air scheduling	Controls
HVAC	Thermal energy storage (TES) controls, chilled water	Controls
HVAC	Economizer tuning (improve free cooling)	Controls
HVAC	Calibration of economizers (tune, repair damper mechanics)	Controls
HVAC	Relocation of outdoor temperature sensor for improved accuracy	Controls
HVAC	RTU economizer	Controls
HVAC	RTU fan variable frequency drives (VFDs)	Controls
HVAC	RTU fan cycling control	Controls
HVAC	RTU strip heat control	Controls

Table A1 (*continued*)

Building System Type	EEM Name	End Use System Element
HVAC	RTU optimal start	Controls
HVAC	RTU optimization package - compressor speed reduction	Controls
HVAC	Furnace fan controls	Controls
HVAC	Modulate flow through heat exchangers (Plate and Frame)	Controls
HVAC	Multiple Air Handling Unit (AHU) fan sequencing to reduce peak coincident load	Controls
HVAC	Add VFDs to secondary loop pumps	Controls
HVAC	Demand Response (DR) RTU controller	Controls
HVAC	Daytime extra cooling controls - concurrent with peak renewable energy generation	Controls
HVAC	Pre-ventilation of spaces prior to renewable generation decrease	Controls
HVAC	Demand Control Ventilation (DCV)	Controls
HVAC	Variable Air Volume (VAV) box, occupancy and setback controls	Controls
HVAC	Zonal DCV	Controls
HVAC	Thermostat setpoint change	Controls
HVAC	Supply air temperature reset	Controls
HVAC	Duct static pressure reset control	Controls
HVAC	Duct static pressure tuning	Controls
HVAC	VAV box minimum flow reset	Controls
HVAC	Small commercial Energy Management System (EMS)	Controls
HVAC	Model predictive control (MPC) HVAC software	Controls
HVAC	HVAC with dynamic energy and demand optimization	Controls
HVAC	Advanced Measurement & Verification (M&V) / Fault Detection and Diagnostics (FDD) services	Controls
Plug loads	Central laptop/monitor control	Controls
Plug loads	Server power management	Controls
HVAC	Server room temperature reset	Controls
HVAC	Enthalpy wheel relief air energy recovery	Support. Devices
HVAC	Exhaust air heat recovery coil coupled with outside air preheating coil	Support. Devices
HVAC	Server closet exhaust retrofit	Support. Devices
HVAC	Chilled water storage - optimized for outside air daytime use and peak renewable generation	Support. Devices
HVAC	Hydronic thermal energy storage	Support. Devices
HVAC	Ice tank thermal energy storage	Support. Devices
HVAC	Phase Change Material (PCM) 'tank' storage	Support. Devices
HVAC	PCM in drop ceiling	Support. Devices
HVAC	Battery storage	Support. Devices
HVAC	Duct work sealant and insulation	Distribution

Table A2
Top-ranked energy efficiency measures (EEMs) per utility partners.

EEM	Brief Description
LED luminaires	Integrated LED fixtures replacing baseline troffers on a one-to-one basis. Efficacy of 110 lm/watt or greater and maximum power of 35 W per fixture.
LED luminaires with occupancy controls	Luminaire level lighting controls (LLLCs) with occupancy sensor on-board each fixture. In private offices the fixtures turn off when vacancy is detected. In open office zones, the fixtures dim to 30% when vacancy is detected, and when an entire zone is vacant all fixtures turn off.
LED luminaires with daylight dimming controls	Continuous daylight dimming via onboard photosensor at each LED fixture to maintain target illuminance setpoint.
Zone level HVAC occupancy controls, setpoint reset	Use of LLLCs and onboard occupancy sensors at each fixture to inform the HVAC system of zone occupancy. When a zone is unoccupied during the workday, implement zone setpoint setbacks (2.8C up for cooling and 2.8C down for heating setpoints).
Zonal demand control ventilation (DCV) by occupancy	DCV based on actual numbers of occupants in space, counted by LLLCs occupancy sensors (some regions require CO2 sensors). Measure designed to maintain CO2 levels below 1000 ppm (assuming 400 ppm ambient) during scheduled occupied hours. Minimum ventilation = 0.25 CMH / 0.1 square meter. DCV ventilation = zone floor area × 0.10 CMH + occupancy number × 8.5CMH.
Intermittent ventilation*	When the variable air volume (VAV) terminal box is in a period of low flow, alternate the box on and off to provide minimum ventilation requirement (staged VAV box operation to provide ventilation (on/off, every 30 min.)
Variable Air Volume (VAV) terminal box minimum retuning	From a baseline of 30% minimum flow setting at the VAV box, re-tune minimum flow to 15%. In operation the actual minimum will be 15% or the outdoor air minimum of 0.010 CMH / 0.1 square meter, whichever is greater.
HVAC temperature setback and lighting power reduction for Demand Response (DR)	Global cooling setpoint adjustment up to 26.1C during DR events. Lighting power universally reduced by 20% during events.
Ceiling fan with programmable control, smart thermostat with reset	Install 1 ceiling fan per 37.2 square meters, assumed to run at 27 W / fan for 1.5 m fans run at 75% speed. Ceiling fans turn on automatically and cooling setpoint increases 2.2C during occupied hours when the zone is in cooling mode and using chilled water for at least 1 h (i.e. fans do not operate when in economizer mode with outside air only).
Demand response (DR) controls with smart ceiling fans	Same as above, with a cooling setpoint increase of 3.3C, with ceiling fans on, during the DR event.
Chilled water thermal storage time of use (TOU) controls*	Chilled water storage tanks, sized to meet 25% of cooling load for the period of summer peak (i.e. noon – 6PM). Prioritize tank discharge over chiller operation during peak summer pricing. Prioritize charging of tanks via waterside economizer when conditions allow, charging via chiller operation on overnight off-peak otherwise.
Demand response (DR) controls with chilled water	Same as above; additionally prioritize discharge over chiller operation during DR events (when in cooling

(*continued on next page*)

Table A2 (*continued*)

EEM	Brief Description
thermal storage*	mode).
Chilled water return use for outside air preheat	Installation of additional air handler coil for circulation of chilled water return to preheat outside air. Active when outside air temp. lower than chilled water return temp.
Waterside free cooling, (in combination with chilled water thermal storage)*	Run waterside system in economizer mode to generate chilled water without chiller operation (economizer assumed to be integrated). Pump and fans on cooling tower to operate when condenser water supply temp is at or below 7.2 – 8.3C (indicative - will depend on required chilled water supply temp.), to enable provision of chilled water to thermal storage via chilled water circuit. Only recommended for climate zones where wet bulb temp is below 12.8C for 3,000 h or more per year.
ASHRAE Guideline 36 economizer controls	Depending on baseline; reset fixed dry bulb temp. to 20.6C, 23.3F, or 22.8 – 26.1C (varies by CA climate zone) for economizer high limit cut-off.

Asterisk ("*") indicates measures that were used in packages developed for project, but that were not included in the 16 packages covered in this paper.

References

[1] ASE, 2017. Alliance to Save Energy Systems Efficiency Initiative. Going Beyond Zero. A Systems Efficiency Blueprint for Building Energy Optimization and Resilience. Year 2 Report. May 2017.

[2] ASHRAE, 1982. Standard 90a-1980: Energy conservation in new building design - an updated version of ASHRAE 90-75. 1982.

[3] ASHRAE, 2018. ASHRAE Guideline 36-2018. High-Performance Sequences of Operation for HVAC Systems. 2018.

[4] ASHRAE, 2021a. ASHRAE Standard 140-2020 - Method of Test for Evaluating Building Performance Simulation Software (ANSI Approved). 2021.

[5] ASHRAE, 2021b Standard 55-2020 - Thermal Environmental Conditions for Human Occupancy (ANSI Approved). 2021.

[6] ACEEE, 2009. Saving Energy Cost-Effectively: A National Review of the Cost of Energy Saved through Utility-Sector Energy Efficiency Programs. https://library.cee1.org/sites/default/files/library/8570/CEE_Eval_Saving%20Energy%20Cost_Effectively_Sep2009.pdf.

[7] G.L. Barbose, C.A. Goldman, I.M. Hoffman, M.A. Billingsley, The Future of Utility Customer-Funded Energy Efficiency Programs in the United States: Projected Spending and Savings to 2025, Energy Efficiency Journal (2013), https://doi.org/10.1007/s12053-012-9187-1.

[8] CPUC, 2018. RESOLUTION E-4939. Public Utilities Commission of the State of California. October 2018.

[9] CEE, 2020. Consortium for Energy Efficiency. State of the Efficiency Program Industry: Budgets, Expenditures, and Impacts 2020. http://www.cee1.org/annual-industry-reports, posted July 2021.

[10] Commercial Reference Buildings [WWW Document], n.d. Energy.gov. URL https://www.energy.gov/eere/buildings/commercial-reference-buildings (accessed 9.14.20).

[11] DNV GL, 2017. Massachusetts Commercial/Industrial Baseline Framework. Massachusetts Program Administrators and Energy Efficiency Advisory Council.

[12] N. Elliott, M. Molina, D. Trombley. 2012. A Defining Framework for Intelligent Efficiency. American Council for an Energy Efficient Economy (ACEEE). ACEEE Report E125. http://www.aceee.org/research-report/e125.

[13] EnergyPlus, n.d. [WWW Document] URL https://energyplus.net/ (accessed 10.18.21).

[14] EnerNOC, 2015. To-Code Savings Project. Pacific Gas & Electric. Available at California Energy Efficiency Energy Contracts Evaluation Studies Public Document Search. https://pda.energydataweb.com/#!/.

[15] EIA, n.d. U.S. Energy Information Administration. Utility energy efficiency spending and savings declined in 2018 - Today in Energy - U.S. Energy Information Administration (EIA) [WWW Document]. URL https://www.eia.gov/todayinenergy/detail.php?id=42975 (accessed 10.15.21).

[16] EPA, 2008. National Action Plan for Energy Efficiency. Understanding Cost-Effectiveness of Energy Efficiency Programs: Best Practices, Technical Methods, and Emerging Issues for Policy Makers. Energy and Environmental Economics, Inc. and Regulatory Assistance Project. Environmental Protection Agency. 2008. www.epa.gov/eeactionplan.

[17] J.D. Feng, H. Cheng, Comparison of construction and energy costs for radiant vs. VAV systems in the California Bay Area. 2018.

[18] M. Frankel, K. Madison, J. Lerond, Final Report on Energy Impacts of Commercial Building Code Compliance in Rhode Island, New Buildings Institute. (2017).

[19] Todd D. Gerarden, Richard G. Newell, Robert N. Stavins, Assessing the Energy-Efficiency Gap, Journal of Economic Literature 55 (4) (2017) 1486–1525, https://doi.org/10.1257/jel.20161360.

[20] Kenneth Gillingham, Karen Palmer, Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence, Review of Environmental Economics and Policy 8 (1) (2014) 18–38, https://doi.org/10.1093/reep/ret021.

[21] K. Hawxhurst, J. Williams, A. Pollman, A. Gannon, Renewable-powered HVAC with thermal storage, ASHRAE Journal 59 (2017).

[22] Hoffman, Ian M., Charles A. Goldman, Gregory Rybka, Greg Leventis, Lisa Schwartz, Alan H. Sanstad, and Steven Schiller. Estimating the cost of saving electricity through U.S. utility customer-funded energy efficiency programs, Energy Policy, Volume 104, Pages 1-12, ISSN 0301-4215. 2017 https://doi.org/10.1016/j.enpol.2016.12.044.

[23] IEA, 2017. International Energy Agency Methodology for Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation (Annex 56). Energy in Buildings and Communities Programme. March 2017.

[24] IES, 2020. Illuminating Engineering Society /ANSI RP-1-20, Recommended Practice: Lighting Office Spaces. New York, NY. 2020.

[25] Kiatreungwattana, 2016. Kiatreungwattana, Kosol, Michael Deru and Jason Degraw, National Renewable Energies Laboratory. GSA Green Proving Ground Smart Ceiling Fans White Paper. U.S. General Services Administration. July 2016.

[26] Kaam, 2017. Kaam, S., Raftery, P., Cheng, H., Paliaga, G. Time-averaged ventilation for optimized control of variable-air-volume systems. Energy and Buildings 139, 465–475. 2017 https://doi.org/10.1016/j.enbuild.2016.11.059.

[27] Kirshenbaum, 2017. Optimized Energy Recovery. ASHRAE Journal 59, 30–40. 2017.

[28] Knight, Patrick, Bruce Biewald, and Kenji Takahashi. The cost of energy efficiency programs: Estimates from utility-reported datasets, Energy, Volume 239, Part E, 2022, 122448, ISSN 0360-5442. 2022 https://doi.org/10.1016/j.energy.2021.122448.

[29] Langevin, Jared, Chioke B. Harris, and Janet L. Reyna. Assessing the Potential to Reduce U.S. Building CO2 Emissions 80% by 2050. Joule 3, 2403–2424. Elsevier Inc. October 16, 2019 https://doi.org/10.1016/j.joule.2019.07.013.

[30] Larson, 2017. An Alternate Take on Airside Economizing. ASHRAE Journal 59, 36-38,40-41. 2017.

[31] Li, Cheng, Tianzhen Hong, and Da Yan. An insight into actual energy use and its drivers in high-performance buildings. Applied Energy, Volume 131, Pages 394-410, 2014. ISSN 0306-2619. 2014. https://doi.org/10.1016/j.apenergy.2014.06.032.

[32] A. Lipczynska, S. Schiavon, L.T. Graham, Thermal comfort and self-reported productivity in an office with ceiling fans in the tropics, Building and Environment 135 (2018) 202–212, https://doi.org/10.1016/j.buildenv.2018.03.013.

[33] Mass Save, n.d. [WWW Document] MassSave.com URL. https://www.masssave.com/-/media/Files/PDFs/Partners/2022—Business-Program/Business-Partner-Event-Deep-Energy-Retrofit.pdf?la=en&hash=730DB7D0874CBB7999A065FEBBF6B9AE161747A2 (accessed 3.11.22).

[34] Mathew, 2021. Mathew, P., Coleman, P., Regnier, C., Shackelford, J., Kubischta, D., Zaleski, S., & Dressel, B. Package deals for deep savings: Scaling deep retrofits in commercial buildings with integrated systems packages. Lawrence Berkeley National Laboratory. 2021. Retrieved from https://escholarship.org/uc/item/3t11w8bj.

[35] Mejia, A., Mahone, D., Saiyan, A., Dirr, N., Rogers, C. Savings To Code: Looking to Whole Systems for Implementing Existing Conditions Baselines. Presented at the ACEEE Summer Study on Energy Efficiency in Buildings. 2016.

[36] Navigant, 2019. 2019 Energy Efficiency Potential and Goals Study. California Public Utilities Commission. 2019.

[37] C. Porras-Amores, S. Dutton. Assessing the Energy and IAQ Potential of Dynamic Minimum Ventilation Rate Strategies in Offices, in: Proceedings of the Symposium on Simulation for Architecture & Urban Design, SimAUD '15. Society for Computer Simulation International, San Diego, CA, USA, pp. 172–181. 2015.

[38] Prototype Building Models | Building Energy Codes Program, n.d. [WWW Document] URL https://www.energycodes.gov/prototype-building-models (accessed 10.18.21).

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

[40] C. Regnier, K. Sun, T. Hong, M.A. Piette, Quantifying the benefits of a building retrofit using an integrated system approach: A case study, Energy and Buildings 159 (2018) 332–345, https://doi.org/10.1016/j.enbuild.2017.10.090.

[41] C. Regnier, P. Mathew, A. Robinson, P. Schwartz, J. Shackelford, T. Walter. Energy Cost Savings of Systems-Based Building Retrofits: A Study of Three Integrated Lighting Systems in Comparison with Component Based Retrofits (No. 1503667). 2018. https://doi.org/10.2172/1503667.

[42] RSMeans Online, n.d. [WWW Document] URL https://www.rsmeansonline.com/ (accessed 10.18.21).

[43] Seattle City Light, 2018. [WWW Document]Deep Retrofit Pay for Performance. A How-to Guide & User Manual for Commercial Customers.

[44] J. Shackelford, Robinson, A., Rubinstein, F. GSA Green Proving Ground Retrofit Demonstration of LED Fixtures with Integrated Sensors and Controls. U.S. General Services Administration. 2015.

[45] R. Sherman, H. Naganathan, K. Parrish. Energy Savings Results from Small Commercial Building Retrofits in the US. Energies 14, 6207. 2021. https://doi.org/10.3390/en14196207.

[46] J. Wei, J. Rubinstein, J. Shackelford, Robinson, A. GSA Green Proving Ground Wireless Advanced Lighting Controls Retrofit Demonstration (No. LBNL-183791, 1469136). 2015. https://doi.org/10.2172/1469136.

[47] FACT SHEET: President Biden Takes Executive Actions to Tackle the Climate Crisis at Home and Abroad, Create Jobs, and Restore Scientific Integrity Across Federal Government [WWW Document]. The White House. URL https://www.whitehouse.gov/briefing-room/statements-releases/2021/01/27/fact-sheet-president-biden-takes-executive-actions-to-tackle-the-climate-crisis-at-home-and-abroad-create-jobs-and-restore-scientific-integrity-across-federal-government/ (accessed 10.15.21).

[48] Zhai, John, Nicole LeClaire and Michael Bendewall. Deep energy retrofit of commercial buildings: a key pathway toward low-carbon cities, Carbon Management, 2:4, 425-430. 2011. DOI: 10.4155/cmt.11.35.